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

Pisa, April 30, 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(10²) what inferred from luminosity
- Explanation: substantial amount of matter not emitting light (Dark) must exist







DM-TPC: a new approach to dir Sloan Digital Sky Survey/Spitzer Space Telescope

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Strong evidence for DM

Vera Rubin et al. (1979)

- Study of rotational curve of spiral galaxies
 - Newtonian prediction for orbital velocity of galaxies

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \Longrightarrow \boxed{v \propto \frac{1}{\sqrt{r}}}$$

- 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/STScl; ESO WFI; Magellan/U.Arizona/ D.Clowe et al Optical: NASA/STScl; Magellan/U.Arizona/D.Clowe et al.;



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DM-TPC: a new approach to direct

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 <u>energy</u>
 - 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

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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, Xe, Ar, CsI, NaI, CF₄, ...
- Very challenging measurements
 - Very low-energy recoils (10-100 keV), very weak interactions, many backgrounds

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Present DM searches



- Many experiments engaged in direct detection of DM
 - Recent progress: improved cross-section limits $\sigma_{SI} < 10^{-44}$ - 10^{-43} cm²
- 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 v 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

Directional Detectors

 Direction of incoming WIMP is encoded in direction of nuclear recoil



How to detect the direction of recoils?

Recoil energy (keV)

- Low-pressure gaseous detectors
 - A 50 keV F in CF_4 @ 40 torr recoils ~2 mm

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Spin-dependent interactions

- WIMPs can scatter elastically on nuclei via
 - Spin-independet 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

Chattopadhyay and D.P. Roy, Phys. Rev. D 68(2003) 33010 Murakami B. and J.D. Wells, Phys. Rev. D 64 (2001) 15001 Vergados, J., J. Phys. G 30 (2004) 1127

- Weaker limits for spin-dependent interactions
 - Limits on spin-independent x-section: ~10⁻⁴⁴-10⁻⁴³ cm²
 - Limits on spin-dependent x-section: ~10⁻³⁷-10⁻³⁶ cm²

SD searches are promising and complementary to other DM efforts

7 orders of

magnitude!

Current directional DM detectors





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

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The DM-TPC Collaboration

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DM-TPC: detector concept

- Low-pressure CF₄ TPC
 - 50 torr: 40 keV F recoil ~2mm
- Optical readout (CCD)
 - Image scintillation photons produced in amplification region
 - 2D, low-cost, proven technology
- Amplification region
 - Wire planes \rightarrow mesh detector
 - Woven mesh 25µm, 250µm pitch
- CF₄ is ideal gas
 - <u>F: spin-dependent interactions</u>
 - Good scintillation efficiency
 - Low transverse diffusion
 - Non flammable, non toxic

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Animation by AnaMaria Piso Detector concept



Moyea Sortware

The amplification region

Original design: wire planes



Pros: simplicity, high gains (~10⁴-10⁵)

Limitations of wire-based amplification

Wire-based detectors have serious limitations....





ID reconstruction of the recoil: not enough!

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New amplification region: meshes

Additional coordinate at no additional readout cost



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_{recoil} from total scintillation light
 - Integral of CCD signal ($\sigma_{\rm E}/{\rm E}{\sim}10\%$)
- 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 <u>decreases</u> along recoil track
 - Low energy, below Bragg peak

Additional info from PMTs

- 3rd coordinate of recoil (// v_{drift}) through timing
- Trigger



Bragg curve for 80 keV F recoil from WIMP in CF₄

Background rejection

- Excellent rejection of gammas
 - 8 hours run with 8 μCi ¹³⁷Cs inside prototype: no evts
 - Rejection factor ~2/10⁶ or better
- Excellent discrimination against α and e⁻
 - By measuring both energy and length of recoil
- Neutrons
 - Underground cavern
 - Neutron shielding
 - Passive and active
 - Directionality!
- Solar neutrinos
 - Directionality!



DM-TPC: a new approach to

E (keV) 24

Summer 07

First generation prototype



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DM-TPC: 2nd generation prototype



Bragg curve for 5.5 MeV α from $\,^{\rm 241}\!\text{Am}$



- 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 ~ 1-2 mm
 - Resolution << 1mm; diffusion must be contained</p>
- $\hfill\blacksquare$ Resolution vs drift distance measured with 4 α sources



Light yield calibration with alphas

Photon yield/keV as a function of anode voltage



Stable operations for gas gain $\sim 10^4$ - 10^5

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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





NIM A584:327-333,2008

Observation of "head-tail" in F recoils



More quantitative results (DT)

We measure skewness of light yield along wire

$V_{anode} = 2kV (E \sim 1.5 \cdot 10^5 V/cm)$ 300µm gap, 200Torr

α particles with meshes

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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

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Mesh detector: ²⁵²Cf run @ 75 torr

Next step: DM-TPC (10 liters)

- Active volume: 10 liters
 - Each drift volume: 23cm Ø, 25cm drift
 - 2 CCD cameras (top and bottom)
 - 1 year underground at WIPP (NM)
- P~100 torr; 1 year underground
 - Exposure of 2-4 kg-days

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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 replaces (radiopurity)
- DM study -- 1 year run with CF₄
 - 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 ⁴He-CF₄ to enhance n interactions
 - Measure neutron <u>spectrum and direction</u> in underground cavern
 - Can identify 10% point source over bkg
 - Useful input for nearby DM experiments!

WIMP mass (GeV)

DMTPCino: 1-m³ detector

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

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Sensitivity 1 m³ underground

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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DM-TPC: a new approach

Can we find space for it?

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

From J. Kotcher's presenation at HEPAP meeting on 7/14/2007

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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-m³ design and construction; x50 improvement on σ_p^{SD}
- Large O(10³ kg) DM-TPC detector ideal candidate for DUSEL
 - Directionality: unambiguous observation of WIMPs
 - DM detector --> DM observatory for underground WIMP astronomy

