Progress on D³ - Milli, a prototype Directional Dark matter Detector

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CAASTRO/CoEPP workshop – Melbourne U.
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Outline

- Directional detection
- TPCs with GEMs and pixel chips
  - Energy and angular measurements
  - Absolute position measurement
  - Directional neutron detection
- Moving to directional dark matter detection
  - What is different?
  - Impacts on detector requirements
- D³ - Milli design & status
- Summary
Directional Detection

- Earth's rotation causes **daily oscillation of mean direction** of WIMP wind in lab coordinates.
- Reconstruction of recoils gives a preferred direction in galactic coordinates; towards Cygnus.
- No known background should produce such a signal.

[Diagram showing Earth's rotation and recoils]

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But Why Directional Detectors?

Comparing readout strategies

- Coherent neutrino scattering will start to swamp energy-only detectors
- A directional detector will allow us to “see” past this
- Discussion is now underway about different directional detection strategies

From Ciaran O’Hare's iDM talk
Time Projection Chambers (TPCs)

- Particle enters detector interacting with target
- Ionization is drifted to amplification region and read out
- Idea is to build a low pressure Negative Ion (NI) TPC with GEM amplification and pixel chip readout as a unit cell
- This could then be used for scaling up to a large directional detector
GEMs and Pixel Chips

• Gas Electron Multiplier (GEM)
  – Two layers of copper sandwiching a thin (50µm) layer of Kapton (insulator)
  – Acid-etched holes w/ 70µm pitch
  – Single GEM turns 1 electron into 100s - “Avalanching”

Advantages
• Full 3D track reconstruction
• High single electron efficiency which is needed for low-mass WIMP searches

• ATLAS pixel chips
  – Each pixel is a charge integrating amplifier which measures the ionization energy
  – Low noise ~100 e-
  – Adjustable threshold
  – Self-triggering
  – 40Mhz clock
HeCO₂ (70/30) @ 1atm

3 Superimposed events

- High gain and low noise yields detailed 3D images of ionization
  - 2D projections shown
- Powerful background rejection; event separation
- Virtually noise free
- Head/tail information
  - Particle coming from +z or -z

X-ray conversion

α-particle from PO(210) source

Neutron induced recoil from D-D neutron generator

1.92cm

HeCO₂ (70/30) @ 1atm
D³ Timeline

2011 - 2013

D³ - Micro (~1cm³)
1 pixel chip

(planned, still unfunded - unit cell of CYGNUS)

2013

~ 20 cm³

2014

D³ (~1m³)
~400 pixel chips

2 x 60 cm³

Under construction!

2015

D³ - Milli (~10 liters)
4 - 16 pixel chips (NID w/ SF₆)

8 x 40 cm³
D³ - Micro (2011-2013)

- First prototype at U. Hawaii
  - ~ 1 cm³ detector volume
  - Used for performance testing
  - Double GEM amplification
  - Readout
    - Copper pad – for initial gain calibration
    - ATLAS FE-I3 pixel chip
- Very stable - > 1 year operation
Performance Studies – Gain/Energy

- Ionization collected by copper pad and sent through analog electronics chain
- Gain stable to a few % for weeks
- Need to repeat this study with SF₆

Asymptotic gain resolution values plotted vs. ionization energy
- Pixel chip can't do better

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Graph showing gain vs. GEM voltage for Fe(55), ArCO₂, and HeCO₂.

Graph showing energy resolution vs. energy for Fe(55) escape and main peaks, and alpha particles.
Angular and Energy Resolution (FE-I4)

- Three PO(210) alpha particle sources
  - Different z positions gives z dependent calibration
  - Used for monitoring gain stability
- Done with 2cm alpha tracks segments

- Less than 1-degree angular resolution w/ 15 cm drift
- Energy resolution consistent with gain resolution measurements

HeCO$_2$ (70/30) @ 1atm

Source 3  Source 2  Source 1

I. Seong
Absolute Position Measurement

- Plot charge profile, $Q_{px}$, vs. distance from center of track; fit with Gaussian
- Take width of Gaussian and plot vs known $z$ based on 3 known source positions
  - This gives a one-to-one relationship between $z$ and charge profile width
- Allows for absolute $z$ within ~1cm; even for short, 2mm, tracks

3D – fiducialization allows for background free running

3D graph showing $z$ vs. $Q_{px}$ for different track widths and neutron source presence:

- Neutron source present
- Neutron source not present

Mesh at $z = 15$ cm

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<th>Neutron Source</th>
<th>Tracks / Day (Day$^{-1}$)</th>
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<td>Overflow</td>
<td>0.1715</td>
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</table>

8mm tracks
2mm tracks

Directional Neutron Detection

• Energy and angular resolution allow reconstruction of “neutron wind” in lab... just like the “WIMP wind”
• Cf(252) source - ~MeV neutrons give ~100s keV He recoils
  – Result is a few mm track length @ 1atm

HeCO$_2$(70/30) @ 1atm

Background Run

Source Run

I. Seong
What's Different About Detecting Dark Matter?

- WIMPs give less energy to targets ➔ Shorter recoil tracks
- Solution: lower the gas pressure
  - 2 main issues when this is done

  **Steel vessel** ➔ **Acrylic vessel**
  - **Sparking**

  **Neutron detection** ➔ **Dark matter detection**
  - **Diffusion**

  **Electron gas** ➔ **Negative Ion (NI) gas**
  - **Destroys tracks**

Activity of vessel material will also be a major issue when building a large detector

Negative Ion gases diffuse less, have slower drift velocities, and less gain
WIMP Recoil Energy Spectra

- Good rule of thumb is for a WIMP of mass $x$ GeV the detector threshold should be $x$ keV or less; around the mean of the recoil distribution
- Energy transfer is maximized when the target mass equals WIMP mass
WIMP Recoils (SRIM)

20keV He in 10 torr SF₆ + 50 torr He

- For low mass WIMPs helium may be a good target

5keV He in 10 torr SF₆ + 50 torr He

- Is directionality at 5keV possible?
Neutron Study

HeCO$_2$ (70/30) @ 1atm

- What do ~20keV 2-3 mm tracks look like?
- Can see asymmetry in the energy deposition
- Need to study even lower energy recoils than this
- Goal being to have directionality for the lowest energy recoils possible
- Also must quantify background discrimination at low energies
Efficiency with Neutron Recoils

- Data from directional neutron detector deployed at SuperKEK $e^+e^-$ collider

- With tight event selection that rejects all of the large x-ray background, 50% efficiency for nuclear recoils is at 15 keV

  - This will likely be much better in a low background detector

20 keV recoil tracks that are 2-3 mm long should give a strong directional signal for WIMPs as well
• 4cm drift w/ triple GEM gain stage

• Working well in electron gases

• SF$_6$ studies in progress
  - Noise has been a major factor
  - Sparking
  - SF$_6$ contamination when moving back to electron gases

• Currently modifying so source can be turned on/off
• FE(55) source – 5.9keV ; HeCO$_2$ (70/30) @ 1atm

• Triple GEM resolution is nearly the same as double GEM @ high gain
D³ – Milli Acrylic Vacuum Vessel

- Wooden stands were made to line endplates up with vessel
  - Field cage slides in; make connections
  - Push endplates against vessel
  - Insert rods and tighten nuts

- SHV/LV endplate
  - GEM power
  - Gas in/out
  - Readout electronics

- 30kV endplate
  - Field cage power

KF-40 x 7

1.2m
• Acrylic vessel > 3 orders of magnitude higher outgassing than stainless R&D vessel
• May have to flow gas for low pressure measurements
  – Others have shown gain in low pressure SF$_6$ in acrylic

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Pumpdown curve

Outgassing curve

Temperature fluctuations

~ 1 day

~ 3 weeks
D³ – Milli Field Cage

- Aluminum rings w/ 2cm delrin spacers
- 30cm w/ 30 kV power supply to start but idea is to maximize the drift length
- Self supporting
  - Will assemble in clean room and place in chamber completed
- Will have 12 contact points with acrylic tube; should slide easily
- Interfacing with GEM stage is being designed
  - Idea is to mount GEM stage and pixel chip circuit board to field cage
D³ – Milli Unit Cell

- Will start with 1 GEM/chip cell
- Move to 4
  - Have DAQ to do this; USBPIX 3
- Ultimate goal is to instrument entire readout area with 16 chips, or 4 chips with “charge focusing”
  - https://arxiv.org/abs/1304.0507

FE-I4 circuit board

9.5cm
Summary

- TPCs with GEMs and pixel chips are capable of reconstructing nuclear recoils in 3D with high-resolution
- Have demonstrated 3D directional neutron detection with multiple detectors
- Discussed how directional neutron detection is related to directional dark matter detection
  - And what makes it more challenging
- Working on getting gain with R&D setup using SF$_6$ (Negative Ion gas)
- Now constructing our first dedicated directional dark matter prototype, D$^3$ - Milli, as a possible unit cell for a larger directional dark matter detector
Backup
High Energy 3D Nuclear Recoil

- each block: 50x250x250 μm³
- Color: ionization density

Ionization cloud from 1MeV recoiling Helium nucleus
Medium Energy 3D Nuclear Recoil

- each block: 50x250x250 μm³
- Color: ionization density

Ionization cloud from $E_{ee} \sim 25$keV recoiling Helium nucleus
3-m³ for 3 years

WIMP mass [GeV/c²]

Preliminary