Directional detection of Dark matter

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Directional Detection of Dark Matter

State of the art:
direct detection requires high rejection factor against background, which need to be very precisely understood (radiopurity of materials, neutrons, …)

Alternative strategy:
having a clear and unambiguous signature for WIMP

How? The solar system rotates around the center of the Galaxy, through a halo of WIMPs, and towards the Cygnus constellation.

More precisely the Deneb star

Background can not mimic such genuine events

WIMPs events should point towards Cygnus constellation (a wind of WIMPs)

Strategy:
• use direct detection
• reconstruct Energy AND Track of the recoil nuclei
• Prove that the signal “comes from Cygnus”

D. N. Spergel, PRD 1988
Directional DM detection - isothermal spherical halo

Both the WIMP flux and the recoil events show a strong direction dependency towards Cygnus constellation ($\ell = 87.5^\circ, b = 1.3^\circ$)

Strong forward/backward asymmetry
Directional DM detection - ellipsoidal halo

Going from spherical DM halo to 3-axis ellipsoidal DM halo: does not affect *qualitatively* the directionality of the signal

In principle, properties of the galactic halo could be also constrained

*J. Billard et al., 2009*
Requirements for a directional DM detector

WIMP

Need to measure (E,L, Θ, φ)

• Low Energy recoils
• 3D tracks

Gazeous detector (TPC)
Low mass target

Planned or ongoing experiments:
Drift (CS₂), DM-TPC (CF₄), NEWAGE (CF₄), MIMAC (³He, CF₄, C₄H₁₀)

First exclusion from directional detection (NEWAGE): Miuchi PLB 2007

Challenge: measure low energy 3D tracks (at low pressure)
The MIMAC project

A multi-chamber detector for Dark Matter
- Matrix of chambers (correlation)
- $\mu$TPC : Micromegas technology
- Track-ionization Energy measurements
- Multi-target detector (H, He, F)

$\sigma(A)$ dependancy
- High or low pressure regime

MIMAC WIMP/background Discrimination based on:
- Energy (ionization)
- Track
- Direction (Cygnus)
# MIMAC Collaboration

<table>
<thead>
<tr>
<th>Institution</th>
<th>Members</th>
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<tr>
<td><strong>LPSC (Grenoble)</strong></td>
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## Multi-Target detector for spin-dependent detection

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Gaz</th>
<th>Odd nucleon</th>
<th>J</th>
<th>$&lt;S_p&gt;$</th>
<th>$&lt;S_n&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>$C_4H_{10}$</td>
<td>p</td>
<td>1/2</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$^3$He +$C_4H_{10}$</td>
<td>n</td>
<td>1/2</td>
<td>-0.05</td>
<td>0.49</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>CF$_4$</td>
<td>p</td>
<td>1/2</td>
<td>0.44</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

- Spin dependent Interaction (complementarity)
- Interaction with n (He) or p (F,H)
- Low mass target → Low energy recoils

First phase: focus on low energy Helium ions

$E_{recoil} < 6$ keV
A μTPC for Dark Matter

Micromegas with pixellized anode (x,y): 3 cm x 3 cm

Main issues:

Measured Energy ≠ $E_{\text{recoil}}$
and
Track Projection ≠ 3D Track
Energy measurement: Quenching factor

Recoil energy is shared among:

- Scintillation
- Heat
- Ionization

Ionization Quenching factor:

\[ Q = \frac{E_{\text{ionization}}}{E_{\text{recoil}}} \]

- Helium Quenching factor is predicted by Lindhard theory
  ... but need to be measured!
- Key point for Dark Matter to compute recoil energy
Quenching factor measurement: experimental set-up

- ECR ion source developed @ LPSC
- Low energy ion source 1 to 50 keV
- Possibility to produce: p, $^3$He, $^4$He, $^{14}$N, $^{19}$F … ➔ Start with $^4$He
- Calibration with X-ray (Al: 1,486 keV and Fe: 5,97 keV)
Quenching factor measurement: low energy ion

1.5 keV $^4$He

- Ionization energy: 400 eV!
- Energy Resolution ($\sigma/E$): 34%

50 keV $^4$He

- Ionization energy: 35.5 keV
- Energy Resolution ($\sigma/E$): 2%

$^4$He from 1 keV to 50 keV
Quenching factor measurement: low energy ion

Quenching factor @ 700 mbars

- Measurement of $^4$He in 95% $^4$He + 5% $^{12}$C
- Threshold: 300 eV (ioni.) or 1 keV (recoil)
- The response of this $^4$He detector is fully understood from 1 to 50 keV
- Dark Matter range: covered
  

Range of interest for Dark Matter

Quenching factor is needed to compute $E_{\text{recoil}}$ of the nuclei
Tracks: Range vs Energy

Electron track is longer than recoil track (of the same energy)

Full Simulation
- SRIM
- measured Quenching
- Measured resolution (Energy & track)

Clear electron/recoil discrimination, even @ very low energy

Going further (directionnality) requires 3D tracks …

J. Billard et al., 2009
Tracks: 3D track reconstruction strategy

Scan the anode every 25 ns

\[ \sigma_{\text{Diff}} = 200 \ \mu\text{m} \sqrt{L(\text{cm})} \]
\[ v_{\text{diff}} = 26 \ \mu\text{m/ns} \]

Complete electronic system:
ASIC (16 strips channels with mixer & shaper) + FPGA (On-board processing) + DAQ

C. Grignon et al. 2009 (to appear)
3D Track: 5.5 MeV α from $^{222}$Rn

MIMAC Event display

Track 354
φ = 59.2 deg
Θ = 35.5 deg
L = 4.99 cm
3D Track : 5.9 keV electron from $^{55}$Fe

MIMAC Event display

With the 3D reconstruction

E = 200 V/cm
P = 350 mbar
v = 16 μm/ns

Track 45

$\phi$ = 41.6 deg
$\Theta$ = 34.2 deg
L = 7.5 mm

First 3D track of ~6 keV electron !!
... typical of a background event for Dark Matter
Recoil from 144 keV neutrons

Preliminary results!

Amande facility @ IRSN Cadarache
-> Neutron field with energies down to a few keV

Pure isobutane
100 mbar
150 V/cm

(same results in pure methane)

• Possibility to have H as a target
• Separate background from recoils
3D track : next step

Next step:
Measurement of keV Helium recoil
... typical of a signal event for Dark Matter
However, Track will be one order of magnitude smaller
Going to lower pressure (100 mbar)
MIMAC: conclusions and outlooks

• Directional detection offers a **clear signature** for WIMP detection ... providing the detector can measure energy and 3D recoil track

• Helium Quenching factor has been measured at various pressures
  ⇒ Key point for energy measurement

• First tracks measurements in the detector
  ⇒ Alpha used to measure drift velocity
  ⇒ Identification of 6 keV electrons,
  ⇒ e-/nuclei discrimination possible

**Next Steps**
• Neutrons detection @ IRSN Cadarache, in Oct. 2009
  ⇒ neutron beam with an energy down to a few keV
• Phase I : 1 m3 in 2012
Backup slides
Track: 3D reconstruction simulation

• Simulation of 3D Reconstruction (DAQ and Recon. Algorithm)
  • Assumed linear trajectory for recoil tracks
  • $V = 26 \text{ mm/ns}, 300 \mu\text{m pitch}, \sigma_{\text{diff}} = 200 \text{ mm} \sqrt{L(\text{cm})}$

Promising angular resolution for directional detection
3D Track : 5.5 MeV α from $^{222}$Rn

With the 3D reconstruction

Track 354
$\phi = 59.2$ deg
$\Theta = 35.5$ deg
$L = 4.99$ cm
Tracks: Range vs Energy

Electron track is 10 times longer than $^3$He track (of the same energy)
Quenching factor measurement: calibration

1,486 keV X ray (Al)  
5,97 keV X ray (Fe)

$\sigma / E \approx 14\%$  
$\sigma / E \approx 5\%$
3D track : low energy Helium recoils

Amande facility :
@ IRSN Cadarache
-> Neutron field with energies down to a few keV

Experiment starting... tomorrow !
Recoil from 144 keV neutrons

Possible to reconstruct recoils of proton
@ low pressure in isobutane
(same results in pure methane)

Open the possibility to develop a DM directional detector with Hydrogen as a target (pure isobutane).

Multi-target detector
Track: Measurement of electron drift velocity

α source $^{241}\text{Am} +$ collimator (A ~ 1 Bq)

Drift Time

16.5 cm Drift Time (~10 μs)

DATA

Drift time

Magboltz

Data

$\frac{E}{P}(\text{KV.cm}^{-1}/\text{atm})$
Micromegas μTPC : Energy resolution

- Energy resolution of Micromegas μTPC has been measured down to 1 keV

We have shown that:

- It does not depend on pressure
- It does not affect Dark Matter (number of events expected) even at low energy

F. Mayet et al. 2008 (to appear)

Energy measurement of recoils with a $^4$He Micromegas μTPC: fully studied for our purpose (resolution & quenching)
NEWAGE Results : Miuchi, PLB 2007

Fig. 8. Measured (with error bars) and expected (histogram) distribution of the angle between the recoil direction and the WIMP direction. The expected histogram is that with $M_\chi=100\text{ GeV}$, 100–120 keV bin, and $1.36\times10^4\text{pb}$.

Fig. 9. 90% C.L. upper limits on the WIMP-proton spin-dependent cross section (upper) and $\chi^2$ values (lower) as functions of the WIMP mass. The thick solid and dotted lines show the limits obtained with and without the direction information, respectively. Limits from other experiments (DAMA(Xe)[3], DAMA(NaI)[4], NAIAD[5], Tokyo CaF$_2$[7], SIMPLE 2005[10], PICASSO[11], and CDMS[12]) are shown for comparison. The filled squares show the $\chi^2$ minimum values of the best-fit WIMP distribution, the filled-circles show the best-fit flat cos $\theta$ distribution, and the dotted line show the $\chi^2$ values at the 90% C.L. upper limit.
Dark Matter Directional Detection

- WIMPs events should globally come from Cygnus constellation
- Strong forward/backward asymmetry

_B. Morgan et al., PRD 2005_

To reject isotropy:
- 20-70 events (3D+sense)
  Sense -> head/tail effect
- 200-700 events (3D)
- 2000-7000 events (2D)
3D track measurement of an electron of 1.5 keV (X(Al))
3D Track reconstruction

3D track is reconstructed from 25 ns scan of the (x,y) anode. Measure $\Delta X$, $\Delta Y$ and $\Delta Z$. Knowing the drift velocity, $L$, $\theta$ and $\phi$. 

Time:
- $t=0$ ns
- $t=25$ ns
- $t=50$ ns
Energy Calibration of Micromegas

AI: 1.5 keV
49% (FWHM)

Fe: 5.9 keV
32% (FWHM)
Ion source calibration with Si$_3$N$_4$ membrane

Time of flight under vacuum

- Neutral atom after the Silicon nitride membrane
- Method: measuring time of flight for 2 positions of the STOP channeltron
QF measurement: versus Lindhard & SRIM

- Lindhard: pure $^4\text{He}$
- SRIM: simulation of $^4\text{He}$ in 95% $^4\text{He}$ + 5% $\text{C}_4\text{H}_{10}$

Part of energy given to electrons

May be assigned to scintillation


Need to measure He scintillation…
Lindhard prediction for Helium

From J. Lindhard (1963)
Lewin & Smith (1996) parametrization

High Q value for Helium
Need to be measured

$Q(^3\text{He})$ slightly greater than $Q(^4\text{He})$
Cross section $^3$He-χ and event rate in MIMAC-He$^3$ (10kg)

- $0.02 < \Omega_{\chi} h^2 < 0.15$
- Accelerator constrains

Exclusion curve for background $10^{-3}$ kg$^{-1}$jour$^{-1}$

Neutralino mass (GeV/c$^2$)
Complementarity with scalar detection

\[ \sigma_{SD} \text{ and } \sigma_{SI} \text{ not correlated} \]

E. Moulin et al, PLB 614 (2005)143
Direct Detection of SUSY Particles

**Elastic diffusion** $\chi$-quark:

- **spin dependent (axial)**
  \[ \sigma_{SD}(AX) \propto \sigma_{SD}(p) \times A^2 \]

- **spin independent (scalar)**
  \[ \sigma_{SI}(AX) \propto \sigma_{SI}(p) \times A^4 \]

For $^3$He and $^{19}$F: $\sigma_{SD} \gg \sigma_{SI}$