NEWS-G: Search for Light Dark Matter with a Spherical Proportional Counter

P. Knights on behalf of the NEWS-G Collaboration

University of Birmingham, UK

HEP 2021, Thessaloniki (Online)
DM Direct Detection Landscape

- Plethora of evidence for Dark Matter
- Searches for several decades have absence of conclusive evidence in WIMP-preferred region
  - Lee-Weinberg Limit, \(\sim 2\) GeV/c², to \(\sim 1\) TeV/c²
- Much weaker constraints 0.1-10 GeV/c² mass range
- Region has attracted theoretical interest

![Graph showing the direct detection landscape for dark matter candidates with energy threshold, target nucleus mass, and WIMP mass.]
Light DM Detection

- Kinematic matching: **low-mass targets** are **favourable for light-DM detection** by nuclear recoils
- Direct detection using light target gases (H, He, Ne)
- **Favourable ionisation quenching factor**

![Graphs showing 1/σ_{Si} dR/dE_R vs E_R for different target gases and masses](image-url)

$v_0 \approx 220 \text{ km s}^{-1}$

$E_R \propto \text{O(keV)}$

$1/2 = 1 \text{ GeV/c}$

$1/10 = 10 \text{ GeV/c}$

$m_\chi$

$m_N$
NEWS-G Collaboration

New Experiments With Spheres - Gas

Light DM searches with a novel gaseous detector, the spherical proportional counter

NEWS-G Collaboration Meeting
14-18 December 2020
Spherical Proportional Counter

- \( \phi \)O(0.1-1 m) sphere with \( \phi \)O(1 mm) sphere in centre
- Voltage applied to inner sphere
- To first order, \( E \sim 1/r^2 \)
  - Naturally divides detector into drift and avalanche region

Why a sphere?
- Construction with radiopure materials
- Lowest surface-area to volume ratio
- Size independent capacitance
- Large volume with low noise

\[ \vec{E} = \frac{V_1}{r^2} \frac{r_cr_a}{r_c-r_a} \hat{r} \approx \frac{V_1}{r^2} r_a \]

\[ C = 4\pi \varepsilon_0 \frac{r_cr_a}{r_c-r_a} \approx 4\pi \varepsilon_0 r_a \sim 1\text{pF} \]

\( r_c = \text{cathode radius} \)
\( r_a = \text{anode radius} \)

I. Giomataris and G. Charpak in CEA Saclay (sphere was previously a LEP RF cavity)

Single- or multi-anode readout
Pulse-Shape Discrimination

- Rise time selections to:
  - Distinguish point-like versus extended ionisations
  - Fiducialise detector
    - Majority of background from cathode material
    - Can select against near-cathode events
  - Reliant on homogeneous electric field and high electric field at large radii (for charge collection)

Primary Electron Diffusion $\rightarrow$ Rise Time of Integrated Charge

1. X-rays in volume
2. X-rays near cathode
3. Cosmic Muons

$\varnothing$30 cm detector, 1.3 bar He:Ar:CH₄ (51.7:46.4:2.3)
$^{55}$Fe source inside detector

Amplitude [$10^3$ ADU] vs. Rise Time [µs]
Neutron Measurements

- Neutron measurements important for understanding background
  - Also have direct applications
- Method using $N_2$ gas for fast neutron spectroscopy
  - Detector operated in Boulby Underground Lab., UK, for these measurements

See I. Manthos Talk: Friday@15:15

Neutron Measurements in Birmingham - 1.5 bar N$_2$ with ACHINOS

$\phi$30 cm detector
1.5 bar N$_2$

$\alpha$ from $^{222}$Rn chain

Black: Fast neutrons
Red: Thermalized neutrons

$^{\text{IEEE 2019 NSS/MIC 2019}}$

NIMA 847 (2017) 10-14
NEWS-G@LSM First Results

- Ne:CH4 (99.3%:0.7%) at 3.1 bar (280 g)
- 9.6 kg day exposure (34.1 days total)

First results from the NEWS-G direct dark matter search experiment at the LSM


Exclusion at 90% confidence level (C.L.) of cross-sections above $4.4 \times 10^{-37}$ cm$^2$ for a 0.5 GeV/c$^2$ DM particle

Limit set on spin independent WIMP coupling with standard assumptions on WIMP velocities, escape velocity and with quenching factor of Neon nuclear recoils in Neon calculated from SRIM
NEWS-G@SNOLAB

- Next stage of NEWS-G
- Ø140 cm detector
- 4N (99.99% pure) Aurubis copper
  - ~7-25 µBq/kg Th and ~1-5 µBq/kg U
- Operated in both LSM and SNOLAB

Commissioning in LSM

Now installed in SNOLAB
Radioactivity of Copper

- Copper is common material for rare event searches
  - No long-lived radioisotopes
- Background sources:
  - $^{63}\text{Cu(n,}\alpha)^{60}\text{Co}$: fast neutrons from cosmic muon spallation
  - $^{238}\text{U}$ and $^{232}\text{Th}$ decay chains
- ICP-MS and $\alpha$-particle for assay
- Dominant for NEWS-G: $^{210}\text{Pb}$ deposited by $^{222}\text{Rn}$
- Used high-purity electroplating to apply 500 µm layer to inner surface
- Shield detector volume

Assay of NEWS-G 4N copper:

- $^{210}\text{Pb}$: 29±8 mBq/kg

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weight [g]</th>
<th>$^{232}\text{Th}$ [µBq/kg]</th>
<th>$^{238}\text{U}$ [µBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C10100 Cu</td>
<td>-</td>
<td>8.7 ± 1.6</td>
<td>27.9 ± 1.9</td>
</tr>
<tr>
<td>(Machined)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>-</td>
<td>&lt; 0.119</td>
<td>&lt; 0.099</td>
</tr>
<tr>
<td>Electroformed</td>
<td>0.256</td>
<td>&lt; 0.58</td>
<td>&lt; 0.26</td>
</tr>
<tr>
<td>Hemisphere 1</td>
<td>0.614</td>
<td>&lt; 0.24</td>
<td>&lt; 0.11</td>
</tr>
<tr>
<td>Hemisphere 2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Many packages available for detector simulation:

- **Geant4**: for simulation particle interactions with matter
- **ANSYS**: finite-element methods software for electric field calculations
- **Garfield++**: For simulating electron-ion drift and signal calculations
  - Interfaces with Magboltz, SRIM and HEED
- **Simulation framework combines these** with custom calculations to form complete simulation
- In use by NEWS-G, R2D2 and for detector R&D
A Multi-Anode Readout - ACHINOS

- Single anode: **gain and drift fields coupled**
- Idea: **Multiple anodes** located at same distance from centre of detector
- **Gain and drift decoupled**
  - Drift field determined by collective field of all anodes
  - Gain determined by individual anode
- Critical for larger detectors and higher pressure

A resistive ACHINOS multi-anode structure with DLC coating for spherical proportional counters

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JINST 15 (2020) 11, 11

See G. Savvidis Talk: Up next!
ACHINOS Studies

- Extensively studied in simulation
- Explained azimuthal amplitude variations
- Charge sharing between channels
- Possibility to reconstruct interaction position and tracks

![Diagram showing azimuthal angle and amplitude variations with data and simulation overlap.](image)

- 1 bar Ar:CH$_4$ (98:2\%) 2200V on anodes
- $^{55}$Fe Inside

![Graph showing amplitude vs azimuthal angle with near and far anodes highlighted.](image)

- 6 Far Anodes
- 5 Near Anodes

![Map showing position from near vs far with different radii and rise time.](image)

- Radius from rise time
- Position from near vs far

![Map showing 1 GeV muon, 100 Torr with initial electrons and start points.](image)
**NEWS-G@SNOLAB: Physics Potential**

Assumptions:
- Flat background (1.78 dru)
- Exposure 20 kg*days
- Energy window [14 eV_{ee}, 1 keV_{ee}]
- F=0.2, θ=0.12
- SRIM quenching factor

[Graph showing DM-nucleon cross-section vs. m_χ [GeV/c^2]]

1.78 dru

20 kg.days

Ne:10% CH₄
Backgrounds in NEWS-G@SNOLAB

Numbers from A. Brossard, PhD Thesis, 2020
Backgrounds in NEWS-G@SNOLAB

Numbers from A. Brossard, PhD Thesis, 2020
Next Stage of NEWS-G: ECUME

- SNOGLOBE's dominant backgrounds: $^{210}\text{Pb}$ in 4N copper and cosmogenic activation
- **Idea:** Underground fully-electroformed detector
- **ECUME -** an underground-electroformed 140 cm sphere
  - Minimised cosmogenic activation - Electroformed in SNOLAB
  - No machining or welding - grow sphere directly
- Builds on achievements of NEWS-G electroplating
  - ~1 mm/month with target of 8-10 mm

**Status:**
- R&D for 30 cm prototype bath at PNNL
- Full-scale planned to be underway by Autumn 2021
- ECUME is initially dedicated to NEWS-G, but after it will be an electroplating facility available in SNOLAB
DarkSPHERE

- **DarkSPHERE**: 300 cm detector
  - Fully-electroformed underground
  - Water-based shielding
  - 60-anode ACHINOS
  - Light target gases:
    - 5 bar He:C\textsubscript{4}H\textsubscript{10} (27 kg)
- Targeted host: Boulby Underground Lab. UK
- Construction proposed for 2024

**Goal**: Reach $\nu$-floor
- Improved shielding
- Larger mass of gas

Multi-physics potential
- Dark Matter search
- $0\nu\beta\beta$ decay search
- CEvNs physics
Summary

- NEWS-G is shining a light on sub-GeV DM
- SNOGLOBE beginning operation in SNOLAB now
  • Significant developments in detector readout, simulation and larger detector compared to SEDINE
- Future spherical proportional counters also underway
  • ECUME is beginning construction this year
  • R&D on prototype underway
  • DarkSPHERE is future stage, with potential to reach neutrino floor in 2025

More on spherical proportional counters:
- G. Savvidis, Wednesday 17:00
- J. Matthews, Thursday 19:00
- I. Manthos, Friday 15:15
- I. Katsioulas, Saturday 12:55