Search for light Dark Matter with NEWS-G: Status and Recent Developments

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SNOglobe prototype at LSM
New Experiments With Spheres - Gas

Search for DM candidates in 0.1 - 10 GeV range
Direct Detection experiment
- Novel Spherical Gaseous Proportional Chamber
- Light Gases as target (H, He, Ne)
- Better projectile - target kinematic match
- Low energy threshold
- Favourable quenching factor

K. Nikolopoulos / IPRD19, 15 Oct 2019 / Search for light Dark Matter with NEWS-G
The NEWS-G Collaboration

6th collaboration meeting, LPSC, Grenoble, June 2019
The principal of operation

JINST 3 (2008) P09007

The rise time, defined as the time it takes to go from
respectively. The two main analysis parameters that are extracted from the treated pulse are the amplitude,
now proportional to the deposited energy only, and the rise time, defined as the time it takes to go from
a loss in the pulse-height. The latter event (right panels) recorded during the physics-run. Raw pulses are shown on top panels
event (left panels) and
deconvolved pulse. However, this double deconvolution procedure can greatly amplify high frequency noise
and degrade the energy resolution. To avoid this event (left panels) and
detector response was chosen to
to a 150 eV

We show in Fig. 2 the pulse treatment discussed above, applied to a 10 keV
drift towards the sphere at ground (cathode) within seconds, more than 50 % of the signal
of secondary ionizations, the acquired signal can be expressed as follows:

Despite ions drifting towards the sphere at ground (cathode) within seconds, more than 50 % of the signal

$E = \frac{V_0}{r^2} \frac{r_1 r_2}{r_2 - r_1} \approx \frac{V_0 r_1}{r^2}$

$C = \frac{4\pi \varepsilon}{r_2 - r_1} r_1 r_2 \approx 4\pi \varepsilon r_1$

$r_1 = \text{anode radius}$

$r_2 = \text{cathode radius}$

Detector volume naturally divided in a “drift”
and an “amplification” volume.
Spherical Proportional Counter

First Spherical Proportional Chamber made out of LEP RF Cavities

- Large Volume
  - Small number of electronic channels
- Low Energy Threshold
  - Low Capacitance
  - High Gain
- Lowest surface to volume ratio
- Fiducial volume selection
  - Through pulse shape analysis
- Flexible (pressure, gas)
- Simple sealed mode

Detection of fluorescence X-rays

\[ ^{241}\text{Am} \rightarrow (^{237}\text{Np}^*) + ^4\text{He} + 5.6 \text{ MeV} \]

\[ ^{237}\text{Np} \rightarrow 13.9 \text{ keV (L } \alpha \text{)} \]

\[ 17.6 \text{ keV (L } \beta \text{)} \]

Irradiation by a \(^{55}\text{Fe}\) source (5.9 keV)

Resolution (\(\sigma\)) < 9%

\[ 1.45 \text{ keV} \]

\[ 5.9 \text{ keV} \]

\[ 8.0 \text{ keV} \]

\[ 13.9 \text{ keV} \]


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SEDINE: NEWS-G Prototype at LSM

Muon flux [cm^{-2} s^{-1}]

- WIPP/LSBB
- Kamioka
- Soudan
- Y2L
- Boulby
- LNGS
- LSM
- SURF
- SNOLAB
- Jin-Ping

5 $\mu$/m^2/day
4800 mwe

Muon flux as function of depth in kilometres water equivalent (km w.e.)

- Lead 15 cm
- Polyethylene 30 cm
- Copper 8 cm
- SEDINE Ø60 cm SPC

■ NOSV Copper vessel (Ø60 cm)
■ Equipped with a Ø6.3 mm sensor
■ Chemically cleaned several times for Radon deposit removal
First results of NEWS-G with SEDINE at LSM


Gas Mixture: Ne+0.7%CH4 at 3.1 bar
Exposure: 9.6 kg×days (34.1 live-days x 0.28 kg)
**Background Sources and Reduction Techniques**

Muon flux as function of depth in kilometres water equivalent (km w. e.)

- **WIPP/LSBB**
- **Kamioka**
- **Soudan**
- **Y2L**
- **Boulby**
- **LNGS**
- **LSM**
- **SURF**
- **SNOLAB**
- **Jin-Ping**

The flux of radiogenic neutrons can be reduced via material selection. Detector materials with low uranium and thorium content give lower neutron and spallation rates. In addition, detector shielding can be used to reduce the external neutron flux further. Often water or polyethylene layers are installed around the detector setup to effectively moderate the neutrons [169]. Active vetoes are designed to record interactions of muons. The data acquired in the inner detector simultaneously to the muon event is discarded in order to reduce the muon-induced neutron background. Plastic scintillator plates are, for example, used for this purpose [161][170]. This can be improved further by the use of water Cherenkov detectors [171][172] as they provide a higher muon tagging efficiency (full coverage), are efficient in stopping neutrons and, for sufficiently large thickness, the external gamma activity is also reduced. To tag directly the interactions of neutrons, shielding using liquid scintillators can be used [173].

Finally, the analysis techniques described in the previous section can also be applied to reduce the neutron background. The multiple scattering tagging is, for instance, particularly effective with growing size of targets. The fiducial volume selection can also be used, however, it has a smaller effect in the reduction of background for neutrons than for gamma interactions because of the larger mean free path of neutrons.

**NEWS-G at SNOLAB**

- Main experiment to take place at SNOLAB
  - NEWS-G to be installed in Cube Hall

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- Main experiment to take place at SNOLAB
  - NEWS-G to be installed in Cube Hall
NEWS-G is preparing SNOglobe
- Ø140 cm
- assembled and commissioned at LSM
- currently being transferred to SNOLAB

H-rich mixtures
Expected to be sensitive to WIMP masses ~100 MeV
Detector already operating at LSM (commissioning run)

Assumptions
- Flat background (1.78 dru)
- Exposure 20 kgdays
- Energy window [14 eVee, 1 keVee]
- \( F = 0.2, \theta = 0.12 \)
- SRIM quenching factor

Preliminary NEWS-G at SNOLab

3 cm of archaeological lead
22 cm of VLA lead
Stainless steel skin
140 cm pure copper spherical vessel
40 cm high density polyethylene
Electric field homogeneity

Ideally, electric field:
- purely radial
- strength $1/r^2$

Reality more complex, as support structure needed for sensor:
- $E = E(r, \theta)$
- Non-uniform detector response

Improved field uniformity by adding correction electrode

I. Katsioulas et al, JINST, 13, 11, P11006, 2018 10.1088/1748-0221/13/11/P11006
Resistive Glass Electrode

- Spark quenching
- Charge evacuation
- Advantages
  - Simple/Robust
  - Symmetric
  - Low material budget
- Material properties
  - Soda-lime glass
  - $\rho = 5 \times 10^{10} \ \Omega \text{cm}$
  - $d = 2.1-2.25 \ \text{g/cm}^3$
  - $A = 14.5 \ \text{mBq/g}$

### Irradiation with 5.9 keV X-rays

- $^{55}\text{Fe at 90°}$
- $^{55}\text{Fe at 180°}$

### Irradiation with 6.4 keV X-rays

- $^{55}\text{Fe at 90°}$

### Graphs

- Graph 1: Counts/40 ADU
- Graph 2: Amplitude [10^3 ADU]
- Graph 3: Amplitude [10^3 ADU]

### Images

- Anode: Ø2-6mm, 2-5mm, 2-30mm
- Insulated Wire
- Glass tube
- Metallic rod

### Irradiation Details

- He:Ar:CH₄ (92:5:3)
  - 1 bar
  - $HV_1=1450\ \text{V}$
  - $HV_2=200\ \text{V}$
  - 2 mm Ø anode

- He:Ar:CH₄ (87:10:3)
  - 2 bar
  - $HV_1=2350\ \text{V}$
  - $HV_2=0\ \text{V}$
  - 2 mm anode

### Advantages

- Simple/Robust
- Symmetric
- Low material budget
Charge Collection in low electric field

- Gain and drift velocity both depend on $E/P$
- At large radii
  - Low drift velocity
  - Susceptibility to attachment
- Crucial aspects
  - Electric field magnitude
    - depends on anode voltage and radius
  - Gas quality

\[
\ln(G) = \int_{E(r_1)}^{E(r_2)} \alpha \left( \frac{E}{P} \right) \frac{dr}{dE} dE
\]

\[
v_{\text{drift}} = \mu \frac{E}{P}
\]

\[
E(r) \approx \frac{V_0}{r^2} r_1
\]

Magboltz study on gas properties and sensitivity to contaminants
Multi-anode sensors: Achinos

- Achinos: Multiple anode balls place at equal distances on a sphere
  - Same gain but increased field at large radii
  - Decoupling Gain and Drift
    - Amplification tuned by anode radius
    - Volume electric field tuned by structure size and number of anodes
  - Anodes can be read out individually
  - TPC-like capabilities

- Prototypes: 5, 11, 33 metal balls $\varnothing2\text{mm}$ successfully operated
- 3D printed Achinos sensors built and operated

\[ \frac{|E_{11}|}{|E_1|} \sim 9 \]
Achinos second generation modules

3D design

Measurement of the 5.9 keV $^{55}$Fe X-ray line

- Good energy resolution
- High pressure operation (~2 bar)
- Resistive layer materials tested:
  - Araldite/Graphite, Araldite/Cu
  - Polymer resistive paste
  - DLC (Diamond Like Carbon)

He:Ar:CH$_4$ (56:37:7)
455 mbar
HV1 = 1100 V, HV2 = -100 V
2 mm Ø anodes
Contaminants: O₂, H₂O, electronegative gases
Filtering with: Getter, Oxysorb
Filtering in a gas re-circulation system
▶ SAES MicroTorr Purifier (MC700 902-F)
▶ Incorporated with Residual Gas Analyser
Improved filtering efficiency in large sphere
A powerful UV laser capable of extracting 100s of electrons

- 213 nm laser used to extract primary electrons from wall of SPC
- Photo detector in parallel tags events and monitors laser power
- Laser intensity can be tuned to extract 1 to 100 photo electrons


Scheme of the experimental set-up
Modelling Single Electron Response

- N photo-electrons are extracted from the surface of the sphere: Poisson
- Each photo-electron creates S avalanche electrons
- Sum the contributions of all N photo-electrons: N\textsuperscript{th} convolution of Polya
- The overall response is convolved with a Gaussian to model baseline noise

Low laser intensity (μ ~ 0.2)

Fit results

θ = 0.09 ± 0.02

<\textit{G}> = 30.26 ± 0.21 ADU

χ\textsuperscript{2}/ndf = 0.97
Measurements of gas properties

- $^{37}$Ar produced by irradiating Ca power with a high flux of fast neutrons
- Together with laser calibrations, can find $W$ (mean ionization energy) with 1% precision for target gas, and set upper limits on $F$ (Fano factor)
- Detector response modelled:
  - Primary ionisation (COM-Poisson)  
  - Avalanche (Polya)  
  
*D. Durnford et al, Phys. Rev. D 98, 103013 (2018)*

*The $W$-value at 2.82 keV was calculated directly from $\langle G \rangle$ and fixed for this fit*
Detector Monitoring

- $^{37}\text{Ar}$ calibrations provide crucial information, but can only be used at the end of a run.
- Within a run, gain fluctuations can be induced by temperature/pressure changes, O$_2$ contamination, sensor damage...
- Laser calibrations provide crucial detector response monitoring during physics runs.
Background in NEWS-G copper

- 4N Aurubis copper (99.99% pure)
  - Spun into two hemispheres
- Copper has no long-lived isotopes
- $^{63}\text{Cu}(n,\alpha)^{60}\text{Co}$ from fast neutrons
  - mostly cosmic muon spallation
- Contaminants: U and Th decay chain traces
  - Measured for NEWS-G ~10 µBq/kg (ICP-MS)
  - $^{210}\text{Pb}$ out of equilibrium - 28.5 mBq/kg (XIA UltraLo)
Copper Electroplating

- PNNL expertise in Cu electroforming crucial
- Detector inner surface electroplated
  - 0.5 mm pure copper plated
  - Good surface quality achieved
- Hemispheres electron-beam welded together
- Suppress backgrounds from:
  - Bremsstrahlung X-rays from $^{210}\text{Pb}$
  - $^{210}\text{Bi}$ β-decays in copper
  - For <1 keV reduced from 4.58 to 1.96 dru
- Copper deposition rate ~36 µm/day
  - Promising: fully underground electroformed detector
Summary

NEWS-G searches for DM candidates with mass 0.1 – 10 GeV

- First competitive results with gas detector
- Improved sensitivity to light Dark Matter
- Lighter targets
- Improved shield /materials/procedure
- Lower energy threshold

Sensor Development

- Better Electric field uniformity
- Higher Electric field in large detectors
- Improved gas quality and monitoring
- Getter, Recirculation, RGA
- Improved calibration and monitoring
  - Laser
  - $^{37}\text{Ar}$
- Many physics opportunities!
Additional Slides
Searching for light DM: Recoil Energy

Recoil energy during DM scattering, $E_R$:

$$E_R = \frac{1}{2} m_\chi u^2 \frac{4m_\chi m_N}{(m_\chi + m_N)^2} \frac{1 + \cos \theta}{2}$$

max $E_R$: head-on-collision and $m_\chi=m_N$
Searching for light DM: Quenching Factor

Quenching factor: fraction of ion kinetic energy dissipated in a medium in the form of ionization electrons and excitation of the atomic and quasi-molecular states.

Direct detection experiment using light gases as target (H, He, Ne)
- Better projectile-target kinematic match
- Favourable quenching factor

Plot by I. Katsioulas
**SEDINE: Data taking conditions**

- **Target:** Neon + 0.7% CH₄ at 3.1 bar (282 gr)
- **Run time:** Continuous data taking for 42.7 days
  - **Exposure:** 34.1 live-days x 0.282 kg = 9.6 kg.days
- **Anode high voltage 2520 V, no sparks**
  - **Absolute Gain ~3000.**
  - **Loss of gain 4% throughout the period**
- **Sealed mode, no recirculation.**
- **Read-out:** Canberra charge sensitive preamplifier (τ_RC=50 µs)
- **Calibration:** $^{37}$Ar gaseous source, 8 keV Cu fluorescence line, AmBe neutron source
SEDINE: Background simulation

- **Anticipated main backgrounds:**
  - **Volume:** Compton electrons
    - $^{208}\text{Tl}$ and $^{40}\text{K}$ in the rock
    - $^{238}\text{U}$, $^{232}\text{Th}$, and $^{60}\text{Co}$ copper shell/shielding
  - **Surface:** Radon decay products
    - **Chemical Cleaning (nitric acid):**
      - $>200\text{eV}$: 180 mHz $\rightarrow$ ~2 mHz
      - $<200\text{eV}$: 400 mHz $\rightarrow$ ~20 mHz

- **Pulse simulations include:**
  - Electric field (FEM)
  - Diffusion (Magboltz)
  - Avalanche process
  - Signal induction
  - Preamplifier response

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SEDINE: Event Selection

- Analysis threshold: 150 eVee (~720 eVnr)
- 100% trigger efficiency (threshold @ ~35 eVee)
- Optimised Signal Region determined with Boosted Decision Tree (8 candidate masses)
- 1620 events selected in preliminary ROI
  - Failed BDT
  - Pass 0.5 GeV BDT: 15 events
  - Pass 16 GeV BDT: 123 events
  - Pass BDT for other masses