Detector Response Modelling Of NEWS-G Dark Matter Search Experiment

Yuqi Deng
Supervisor: Marie-Cécile Piro
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NEWS-G: New Experiments with Spheres-Gas

- NEWS-G: a collaboration developing spherical proportional counters (SPC) for different particle physics studies, including search for low-mass dark matter

![Diagram of a spherical proportional counter]

- **Grounded copper shell**
- **Grounded copper rod**
- **Light target Gas:** H, He, Ne
- **Sensor (Anode):** 2030V

**HV**

**Pre-amp**

**Digitizer**

**Computer**

**Primary Ionization**
Electrons drift towards centre due to electrostatic force applied by the sensor

**Secondary Ionization:**
Primary electrons gaining enough kinetic energy under high Efield near anode can ionize secondary ion/electron pairs

**Induce current**
Secondary positive ions drift away from sensor

**Current signal**

**Pre-amplifier response**

**Voltage signal**

**Digitizer**
• NEWS-G: a collaboration developing spherical proportional counters (SPC) for different particle physics studies, including search for low-mass dark matter

SPC operating principles

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**SPC operating principles**

- **Pre-amp**: Amplifies the induced charge from the sensor.
- **Digitizer**: Converts the amplified signal into a digital format.
- **Computer**: Processes the digitized signal for analysis.

**Primary Ionization**

Electrons drift towards the centre due to electrostatic force applied by the sensor.

**Secondary Ionization**

Primary electrons gaining enough kinetic energy under high E-field near the anode can ionize secondary ion/electron pairs.

**Secondary positive ions**

Drift away from the sensor.

**Induced Current**

Current signal generated from the ionization process.

**Pre-amplifier Response**

Amplifier signal before digitization.

**Digitizer**

Converts the amplified signal into a digital format.
- NEWS-G: a collaboration developing spherical proportional counters (SPC) for different particle physics studies, including search for low-mass dark matter.
Physics and non-physics data were taken with a 1.35m diameter SPC under 135 mbar using pure CH4 at LSM in 2019.

This SPC has been moved and installed in SNOLAB.

U of A is also equipped with 30 cm diameter SPC to perform dedicated studies.
SPC detector response modelling

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- Ar-37 along with pure CH$_4$ was filled in SPC
- Ar-37 emit X-rays at 270 eV and 2.8 keV induced by electron capture in L and K shell
- X-rays are uniformly distributed throughout the detector

Calibration Physics run

Radioactive source: Ar37
UV laser

Electrons drift towards centre due to electrostatic force applied by the sensor

Secondary ionization:
Primary electrons gaining enough kinetic energy under high Efield near anode can ionize secondary ion/electron pairs

Induce current
- Secondary positive ions drift away from sensor
- Pre-amplifier response
- Voltage signal
- Digitizer

Scheme of the experimental set-up


- Compare with data and verify our understanding on the physics happened in our detector, identify different interactions
- Determine cut efficiency/WIMP signal acceptance, further extracting the WIMPs limits on cross section
- Fiducialization (Refer to Carter Garrah’s presentation)
SPC detector response modelling

Step 1: Electric field simulation: Finite element software COMSOL

Step 2: Primary ionization

Step 3: Electron transportation

Electron drift time determined

Step 4: Signal formation

Rise time determined

A simulation work done by Francisco Vazquez de Sola Fernandez

Picture from Georgios Savvidis
SPC detector response modelling

- The Conway Maxwell - Poisson (COM-Poisson) distribution:

\[ P(x | \lambda, \nu) = \frac{\lambda^x}{(x!)^\nu Z(\lambda, \nu)} \]

\[ Z(\lambda, \nu) = \sum_{j=0}^{\infty} \frac{\lambda^j}{(j!)^\nu} \lambda \in \{R > 0\}, \quad \nu \in \{R \geq 0\} \]

- The assumption that the number of primary electrons produced follows poisson distribution doesn’t significantly affect simulation result:

A. Expectation value is a function of deposited energy:

\[ \mu = \frac{E}{W(E)} \]

B. W is the mean energy needed to create electron/ion pair in gaseous detectors.

C. W values being measured in pure CH4 under 135 mbar is 31.2 eV for 2.8 keV X-rays

D. At 2.8 keV, the mean number of primary electrons being ionized is ~ 90

- Initial kinetic energy is not high enough to further ionize gas molecules before entering high E field region
SPC detector response modelling

- Drift velocity of electrons: constant in material under uniform electric field
  - Fick’s 2nd law:
    - Charges diffuse in the gas due to scattering on the atoms of the gas
    - Describes how concentration change with respect to time
    - Expression in 1D: $\frac{\partial \varphi}{\partial t} = D \frac{\partial^2 \varphi}{\partial x^2}$
    - Fundamental solution: $\varphi(x, t) = \frac{1}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$
    - Standard deviation: $\sqrt{2Dt}$
- CERN simulation package: Magboltz:
  - Output: drift parameters: drift velocities, longitudinal/transverse diffusion coefficients
- Monte Carlo method used to determine the electron drift time and locate the position of the events

Step1: Electric field simulation: Finite element software COMSOL

Step2: Primary ionization

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SPC detector response modelling

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Raw pulse 150 eVee event

Deconvolved pulse 150 eVee event

Integrated pulse 150 eVee event

Deconvolve

Detector response

$G = 1000$

$V_e/P = 10000$ Volt/atm

Ampli Canberra

$\tau = 121 \mu s$
The amplitude is almost proportional to the number of secondary pairs created.

- Secondary ionization:
  - PEs reaching high E field region will gain enough kinetic energy from collisions with gas molecules to ionize the gas and create secondary electron/ion pairs
  - Number of secondary ionizations can be parametrized by Polya distribution:
    \[ P(n; \theta) = \frac{(1 + \theta)^{(1 + \theta)}}{\Gamma(1 + \theta)} \left( \frac{n}{\langle n \rangle} \right)^\theta \exp \left[ - (1 + \theta) \frac{n}{\langle n \rangle} \right] \]
  - Rise time: time difference between 75% and 10% of the amplitude
SPC detector response modelling

- **Step 1:** Electric field simulation: Finite element software COMSOL
- **Step 2:** Primary ionization
- **Step 3:** Electron transportation
  - Electron drift time determined
- **Step 4:** Signal formation
  - Rise time determined

### Secondary Ionization:
- PEs reaching high E field region will gain enough kinetic energy from collisions with gas molecules to ionize the gas and create secondary electron/ion pairs
- Number of secondary ionizations can be parametrized by Polya distribution:
  \[
  P(n; \theta) = \frac{(1 + \theta)^{(n + 1)}}{\Gamma(1 + \theta)} \left( \frac{n}{\theta} \right)^\theta \exp \left[ -\left( 1 + \frac{n}{\theta} \right) \right]
  \]

### Rise time: time difference between 75% and 10% of the amplitude
- Represents how much diffusion the charges undergo; Higher starting position results in more dispersion of charges
- Discriminate bulk events and surface events
• **Left:** Laser LSM data show a different mean drift time between high and low laser intensity.

• **Right:** Simulation shows agreement with real data at low laser intensity.

• The decrease of drift time for higher laser intensity run can possibly be explained by space charge effect.
Simulation and real data comparison

Ar37 events rise time simulation: events uniformly distributed in sphere

A physics run performed with both 140 A laser and Ar-37

Same method

A physics run with only Ar-37 events and NO laser events

Simulation for SNOGLOBE

- Tuning the model used to simulate primary ionization or pulse shape doesn’t improve the result;
- The amount of oxygen introduced to the detector is unknown, which can trap electrons and reduce the number of electrons that reach the sensor;
- The significant disagreement is most likely due to the secondary ions created during avalanche (especially from laser events), called space charge effect

Simulation for SEDINE:

1. An SPC of 60cm diameter
2. 99.3% Ne + 0.7% CH4 under 3.1 bar
3. Ar-37 events simulation at 2.8 keV
4. W value measured: 28 eV
5. Simpler sensor geometry allowing for 2D simulation
6. Magboltz and COMSOL were used
• **Ion drift simulation:**

  - The amount of secondary ions from 140 A laser events seen by the detector is known
  - Assuming the diffusion of ions can be neglected
  - Assuming reduced ion mobility $K_0$ of all kinds of ion species is $2.2 \text{cm}^2/\text{Vs}$
  - Drift velocity depends on the Efield:
    \[ K_0 = K \frac{n}{n_0} = K \frac{T_0}{T} \frac{p}{p_0} \]
    \[ v_d = KE \]

• **Ion drift time: 5 ~ 7s**

  - The number of ions exist in the detector can be deduced knowing the laser event rate.

• **Conclusion:** The number of secondary ions live in the detector (before reaching the cathode) is not large enough to increase the overall Efield that can reconcile the primary electrons drift time distribution with the data [Upper right plot]

- Investigation on the created ion species is probably needed (mass spectrometer)
  - The possibility of extremely slow moving ions existence

- Other possibilities:
  - Ions attached onto the DLC material of sensor
  - We plan to use U of A sphere to perform more dedicated laser calibration with different intensity to further investigate the space charge
Extra slides
3.2. SPHERICAL PROPORTIONAL COUNTER

Figure 3.6: Rise time vs Amplitude of the signal for a 200 mbar Ar + CH$_4$ (2%) + $^3$He (0.4%) gas mixture. The horizontal line at 27 $\mu$s corresponds to surface events. [30]

Advantage of SPC

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