MPGD simulation in negative ion gas for direction-sensitive dark matter search

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Outline

• Motivation
  • NEWAGE
    • Negative Ion \( \mu \)-TPC for full-fiducial analysis
    • Needs of MPGD optimization for DM search

• Measurements
  • GEM measurement setup & results in SF6 gas
  • Comparison between ion and electron drift gas

• Simulation work
  • Negative ion drift simulation using Garfield++
    • Try to compare measurement and simulation

• Summary
• **Direction-sensitive** dark matter search at Kamioka Observatory, Japan underground 1000m (1000m below the peak of Mt. Ikenoyama

• uses gaseous TPC “μ-TPC” with μ-PIC and low pressure gas

• expects “WIMP-wind” - directional recoil angle distribution

we are moving toward CYGNUS constellation direction

please see Kentaro Miuchi Sep 2017 RD51 Collaboration Meeting

2D readout $+\Delta T_{sig}$ $+\nu_d = 3D$ position

detect nuclear recoil with DM
Negative Ion TPC for Dark matter search

• Problem:
  • α-ray background from U/Th in glass fiber of μ-PIC (radioactive contamination)

• Solution:
  • production of low-alpha μ-PIC (low contamination of U/Th)
  • full-fiducial analysis with Negative Ion TPC with Negative Ion gas (CS2, SF6, ...)
(Related to this talk)
Negative Ion TPC principle

Several ion species are created and drift at different velocity.

Negative ion drift ($\sim 10^{-2} \text{ cm/μs}$)

Small diffusion in drift

$e^-$ capture?

$SF_6^- \rightarrow SF_6 + e^-$

Multiplication not well understood

Real process is more complicated described in later slide

Use time difference to determine absolute $z$ position $\rightarrow$ full-fiducial analysis

$z = (t_a - t_b) \frac{v_a v_b}{v_b - v_a}$
Negative Ion gas properties

• \( \text{CS}_2 \) (used in \( \text{CS}_2 + \text{CF}_4 + \text{O}_2 \) mixture for DM search)
  • used by DRIFT for DM search (Astroparticle Physics 91 (2017) 65–74)
  • 76.13 g/mol, electron affinity 0.55eV
  • Toxic, flammable, explosive... (not suitable for underground)
    • We hesitate to use this

• \( \text{SF}_6 \)
  • full-fiducial analysis with SF6 was demonstrated in 2015
    (N.S. Phan@CYGNUS2015, N.S. Phan et al 2017 JINST 12 P02012)
  • 146.06 g/mol, electron affinity 1.06eV
  • Inert, colorless, odorless, non-flammable - easy to handle
  • known as Electrical insulator, RPC gas component

We want to use SF6 for DM search...
so it’s need to know MPGD properties in SF6 for optimization
**world-wide MPGD in SF$_6$ activities**

**SF$_6$ and MPGD Overview** (Hirohisa Ishiura CYGNUS gas meeting and others)

| Location      | Gain Device                        | Pressure (Torr) | Max gain | 55Fe Eres($\sigma$) | Ref                  |
|---------------|------------------------------------|-----------------|----------|---------------------|----------------------|
| New Mexico, US| 1mm, 400um GEM (CERN)              | 20-100          | 3000     | 25%                 | JINST12(2017)P02012  |
| Frascati, Italy| 3x 50um GEM (Kapton, CERN)         | 150-370         | 5000     | Landau              | arXiv: 1710.01994    |
|               |                                    | 610 (mixture)   |          |                     |                      |
| Hawai, US     | Thick GEM                          | 40Torr          | 3500     |                     |                      |
| Kobe, Japan   | u-PIC + 100um GEM (LCP, Scienergy), 3x 100um GEM (LCP, Scienergy) | 20-152          | 2000 @ uPIC+GEM 20torr / 10000 @ 3xGEM 120torr | 30% / 50% | arXiv: 1709.06219v1 |
| Wellesley, US | 128, 256um MicroMegas (CERN)       | 30-50           | 300      | ~40%                |                      |
| Sheffield, UK | 400um GEM(UK)                      | 30, 40, 50,(100) | 6000 @30,40torr |                     |                      |

MPGDs were tested in SF6: $\mu$-PIC, Micromegas, GEM (thin & thick)
MPGD optimization for DM search

• But not optimized for DM search
  • Measurement & simulation are required for DM search
• start GEM measurement in SF₆ for a comparison with simulation
  • Because GEM is simple structure and easy to change parameters
  • 50μm and 400μm measurement were done by other groups

We want to know about...

Electron Detachment

Avalanche in SF₆

LCP, 100μm, Scienergy GEM

Iron55 Source

Kapton Windows

DriftMesh(SUS)

ΔV₁

ΔV₂

ΔV₃

HV

HV

HV

HV

1nF

USB oscilloscope UDS-5206S
GEM measurement result in SF$_6$

- **Triple-GEM**
  - $\Delta V_{\text{GEM}}$ and Gas Gain (SF$_6$ 60~120torr)
  - FWHM: $\sim$80%

- **Double-GEM**
  - Gain @ 100 Torr SF6 Double-GEM
  - Gain up to $7 \times 10^3$
  - @100Torr
  - FWHM$\sim$60%

Gain up to $7 \times 10^3$
@100Torr
Comparison between ion and electron drift gas

- **SF$_6$ (ion drift gas)**
  - pure, 100torr
  - FWHM: 80%

- **Ar + C$_2$H$_6$ (electron drift)**
  - (90:10, 760torr)
  - FWHM 20~30%

Both are triple-GEM

- The large difference is energy resolution.
- Is this the key to understand MPGD properties in SF$_6$?

Entries | 3399  
Mean   | 4.614  
Std Dev| 1.972  
Ftemp  | 1.695e-06 ± 5.868e-05 
Signal | 6.081e-07 ± 2.671e-08
Energy resolution and detachment

One hypothesis for energy resolution difference:

- Detachment (electron stripping) position dispersion along to Z-axis (ion drift direction)

Electron detach position dispersion?

not same as other electron drift gas (Ar+C2H6, CF4, ...)

This is one of the key to understand MPGD in negative ion gas

→ Need study by simulation
MPGD Simulation in Negative ion gas

Two Keys for MPGD optimization
• Electron detachment important
• Avalanche process in negative ion gas

Understanding of them
• leads to utilize MPGD in negative ion gas for DM search optimization and analysis

• Need of MPGD Simulation in Negative ion gas
but Not implemented in Garfield++
→ we should modify code to do that
Simulation 1 / 2 - Negative Ion Drift

• As first step, tried to drift negative ion and tracking (get position, velocity, electric field)

• Modify Garfield++ AvalancheMC class to drift negative ion $\text{SF}_6^-$ in negative ion gas ($\text{SF}_6$)

• use $\text{SF}_6^-$ in $\text{SF}_6$ transport data (J. Phys. D: Appl. Phys. 42 (2009) 125203 (6pp))

• tried to drift $\text{SF}_6^-$ in electric field inside GEM Hole first and tracking
Simulation 2 / 2 – Drift and Detachment

• SF$_6$ below 100eV, electron detachment occurs with F$^-$
  • SF$_6^-$ + SF$_6$ → F$^-$ + SF$_5$ + SF$_6$ (1) (right blue)
  • SF$_5^-$ + SF$_6$ → F$^-$ + SF$_4$ + SF$_6$ (2) (right green)
  • F$^-$ + SF$_6$ → e$^-$ + F + SF$_6$ (3) (left red)

• We can expect $10^{-20}$ m$^2$ @ a few eV, eq(1) for F$^-$ production

• check SF$_6^-$ ion has plenty kinetic energy for F$^-$ production?
  (check reaction (1) is possible or not)

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Y. Wang et al. J. Chem. Phys., 91(2254), 1989.
Simulation 2 / 2 – Drift and Detachment

- Track negative ions while in drift
  - Same setup (pressure, $\Delta V_{GEM}$, electric field..) as experiment
  - Kinetic energy (is enough to start $F^-$ production? ~ a few eV)

Result:
- $SF_6^-$ kinetic energy: up to $\sim2.5$ eV inside GEM hole
- Possible enough kinetic energy for $F^-$ production, preliminary step for Electron detachment inside GEM hole

Need confirmation of simulation result

- $\Delta V_{GEM}$
- Electric field
Future plan

• develop methods for simulating detachment and avalanche in negative ion gas

• validation of these methods
  • comparison with measurement and simulation.
  • check we reproduce measurement result in simulation?

Finally
• MPGD optimization with simulation for DM search
Summary

• Negative Ion TPC (NI TPC) is a powerful tool for direction sensitive dark matter search.

• Optimization of MPGD in negative ion gas is important for dark matter search.

• For such an optimization, considering detachment and avalanche process is required and MPGD simulation in negative ion gas is important.

• We have started simulation study of MPGD in Negative ion gas with Garfield++.
backup
Directional Sensitivity

Without directional sensitivity

- Red: June
- Blue: December

very little difference in annual modulation...

With directional sensitivity

Simulated recoil angle distribution

Dashed: DM
Black: neutron

$N_S$: 12 events
$N_f$: 201 events

backward
forward

We can expect to observe ununiformed recoil angle distribution
→ Strong evidence!

2017/10/30
NEWAGE

NEw generation WIMP search with an Advanced Gaseous tracker Experiment
• μ-PIC
N.S. Phan et al 2017 JINST 12 P02012

\[
\begin{align*}
\text{SF}_6 + e^- & \rightarrow \text{SF}_6^- & \text{(attachment, metastable)} \quad (3.1) \\
\text{SF}_6^- & \rightarrow \text{SF}_6 + e^- & \text{(auto-detachment)} \quad (3.2) \\
\text{SF}_6^- + \text{SF}_6 & \rightarrow \text{SF}_5^- + \text{SF}_6 & \text{(collisional stabilization)} \quad (3.3) \\
\text{SF}_6^- & \rightarrow \text{SF}_5^- + \text{F} & \text{(auto-dissociation)} \quad (3.4)
\end{align*}
\]