Study of Negative-Ion TPC using μ-PIC for Directional Dark Matter search

Tomonori Ikeda (Kobe Univ.)
Kentaro, Miuch (Kobe Univ.)
DANIEL, Snowden-ifft (Occidental College)
JEAN-LUC, Gauvreau (Occidental College)
+NEWAGE Group

1. DM Experiments with MPGD
2. NEWAGE
3. Motivation
4. Measurement
5. Summary
1. DM experiment with MPGD
Directional Dark Matter Search with MPGD

- Dark matter is coming to the earth from Cygnus
- Reconstruct 3D track of nuclear recoil using MPGD
- Recoil angle distribution gives strong evidence.

Image of elastic scattering

FT (cos $\gamma_0=0$) $M_{\text{WIMP}}=80\text{GeV}, \sigma_{\text{p-WIMP}}=0.1\text{pb}$

$N_S: 12$ events $N_L: 201$ events

232 km/s

DM

Sun

Earth

Jun. 2nd

Dec. 4th

Cygnus

2015/10/15 MPGD2015 T.Ikeda
IRSN-Cadarache) allowing to select the energy of the neutrons by the angle with respect to a proton beam producing a neutron resonance on a LiF target.

On fig 4 (center and right panel), 3D tracks of nuclear recoils following elastic scattering of mono-energetic neutrons are represented. On the center panel, a 8 keV proton recoil leaving a track of 2.4 mm long in 350 mbar of $^4$He $^4$H $^10$C.

The right panel presents a 50 keV (in ionization) fluorine recoil of 3 mm long obtained in a 55 mbar mixture of 70% CF$_4$ + 30% CHF$_3$.

4. MIMAC at the Underground Laboratory of Modane (LSM)

In June 2012, we have installed the bi-chamber module, at the Underground Laboratory of Modane (LSM), see fig. 5.

The set-up includes a close loop gas system with in-line filtering and is able to reach a vacuum of 10$^{-6}$ mbar. The pressure was regulated at 50 mbar. The gas mixture used was 70% CF$_4$ + 28% CHF$_3$ + 2% C$_4$H$_{10}$.

We have calibrated twice a week by means of fluorescence produced by X generator on thin foils of Cd (3.2 keV), Fe (6.4 keV), Cu (8.1 keV) and Pb (10.5 and 12 keV).

In the fig. 6, we show the low energy calibration obtained, its linearity and the stability of the calibration given by the bin position of the different peaks as a function of time. The first data acquisition started on June 22nd and it has been continuously run and remotely monitored up to October 12th.

In order to characterize the total background of our detector at Modane, we worked without any shielding. Besides the very good stability of the calibration validating the gas circulation,
2. NEWAGE
NEWAGE0.3b’ Detector @Kamioka mine

- Detection volume: 30×30×41 cm³
- Gas: CF₄(76 torr)
- Good for spin dependent DM search

**μ-PIC:** Anode pitch 400 μm  
Gasgain ~10³

**GEM:** Preamplifier (Gas gain ~10)  
LCP 100μm
Latest Result

Conditions **RUN14**
- period: 2013/7/20~8/11, 10/19~11/12
- live time: 31.6 days
- fiducial volume: 28×24×41 cm³
- CF4 gas (76Torr)
- mass: 10.36 g
- exposure: 0.327 kg • days

- Black point is nuclear recoil event
- Gradation color: detector efficiency

**Figure 5.2.2:** Limits of SD cross section, $\sigma_{SD}$ $\chi^{-p}$, as a function of mass of WIMP mass $M_{\chi}$. Red thick solid line is the result of a directional method in this work. Blue thick dotted line is a result obtained with the conventional method for reference. Red thin lines labeled “NEWAGE surface run” and “NEWAGE 2010 (RUN5)” are previous results measured at surface and Kamioka, respectively [83]. Allowed region (DAMA [39]) and upper limits of other experiments are shown for comparison. Green lines are limits set by liquid or solid detectors, blue lines are the limits set by gas detectors with conventional analysis.

**Conditions **RUN14**
- period: 2013/7/20~8/11, 10/19~11/12
- live time: 31.6 days
- fiducial volume: 28×24×41 cm³
- CF4 gas (76Torr)
- mass: 10.36 g
- exposure: 0.327 kg • days

- Black point is nuclear recoil event
- Gradation color: detector efficiency

• the best direction-sensitive limit

(K. Nakamura et al., PTEP(2015)043F01s)
3. Motivation
Background

6.1 High energy backgrounds

Figure 6.1.1 schematically shows the candidates of the high-energy background. Events crossing the outer region of the fiducial area, or the veto area, as is removed by the fiducial-cut. Remaining events are categorized into three types; the events from $+z$ ($2^\circ$), the events from gas ($3^\circ$, $3^\circ'$, $3^\circ''$), and the events from $-z$ ($4^\circ$, $4^\circ'$, $4^\circ''$, $5^\circ$, $5^\circ'$, $6^\circ$, $7^\circ$, $7^\circ'$). These three types of events differ in the drift length. By the gas diffusion, a large TOT-sum is obtained for an event with a long drift length. Figure 6.1.2 shows the simulated TOT-sums assuming three origins of the background sources. The events generated from the $-z$ region (red points; $4^\circ$, $4^\circ'$, $4^\circ''$, $5^\circ$, $5^\circ'$, $6^\circ$, $7^\circ$, $7^\circ'$), have a short drift length and a small diffusion, and result in small TOT-sums. On the other hand, the events generated from the $+z$ region (green points; $2^\circ$) and generated from the gas region (blue points; $3^\circ$, $3^\circ'$, $3^\circ''$) have a long drift lengths and a large diffusions, and result in large TOT-sums.

Figure 6.1.1: Candidates of high-energy background events (500−15000 keV).

- Main background event in $\mu$TPC
  - $7$ in the high energy region
  - $C$ in the low energy region
- $\alpha$-rays (U/Th-chain) from the glass cloth in PI 100µm of $\mu$-PIC is dominant
- We already could $XY$ fiducialize

The Z fiducialization is, if possible, very important.
Self Triggering TPC

Absolute Z-position cannot be known in self-trigger.
Z-fiducialization used by DRIFT


- The first measurement of absolute Z-position in a self-triggering TPC
- Using negative ion gas $\text{CS}_2$ with a few percent $\text{O}_2$

$$z = (t_a - t_b) \frac{v_a v_b}{(v_b - v_a)}$$

MWPC

$\text{CS}_2^-$

30 Torr $\text{CS}_2$
10 Torr $\text{CF}_4$
1 Torr $\text{O}_2$

Minority peak

Table 1: NIPs yield as a function of energy for fluorine recoils, from Ref. [34].

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.001</td>
</tr>
<tr>
<td>1.0</td>
<td>0.002</td>
</tr>
<tr>
<td>1.5</td>
<td>0.003</td>
</tr>
<tr>
<td>2.0</td>
<td>0.004</td>
</tr>
</tbody>
</table>

$\text{Fl}$
Negative Ion Gas Candidates

**CF₄** (electron drift(normal) gas)
- Being used for NEWAGE
- Typical drift velocity: ~cm/μs
- Operation Gas gain 3000 (76Torr)
- Amplifier gain 160mV/pC (ASDchip)

**Negative Ion Gas**

**CS₂**
- Toxic, Volatile, inflammable
- Electron Affinity 0.89eV
- Used with MWPC
- Requirement of gas gain
  \[ \sim 480 \times \frac{76\text{Torr}}{P} \text{ using amplifier (1V/pC)} \]
- Doesn’t have Flourine
  
  We need to add CF₄.

**SF₆**
- Non-toxic, Non-volatile, Nonflammable
- Electron Affinity 1.1eV
- Insulating gas
- High electric field is necessary
- Recently demonstrate with THGEM
  
  [N. Phan talk at CYGNUS2015, June 2015]
- Requirement of gas gain
  \[ \sim 980 \times \frac{76\text{Torr}}{P} \text{, using amplifier (1V/pC), then the amplitude of minority peak will be 15mV at Nuclear recoil (50keV)} \]

Typical drift velocity: \(10^{-2}\)cm/μs

We can use slow shaping time amplifier (good S/N).
4. Measurement
Anode readout

Cathode readout

Drift mesh

GEM

μ-PIC (10×10cm)

NEWAGE0.1c detector

Drift mesh (SUS)

GEM (10×10cm) LCP 100um

μ-PIC (10×10cm)

Amplifier 1.1V/pC or 160mV/pC
4.1 $\text{CS}_2$
Test CS2 with u-PIC+GEM @Occidental College

- CS2 76Torr and 38Torr give more than 1000 total gain!
μ-PIC+GEM system with CS2 worked very well.
Adding O₂ gas, we will be able to observe minority peak.
4.2 $SF_6$
test SF6 with uPIC+GEM @ Kobe Univ.

waveform

252Cf Nuclear Recoil

E = 1100 V/cm  
Anode = 630V  
ΔGEM = 650V  
Amp: $\tau = 1\mu s$

E = 674 V/cm  
Anode = 539V  
ΔGEM = 363V  
Amp: $\tau = 1\mu s$
SF$_6$ Gas Gain

- Total gas gain is about 300.
- When we improve the amplifier, this gas gain is sufficient. Then minority peak will be appeared.

<table>
<thead>
<tr>
<th>hist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
</tr>
<tr>
<td>Prob</td>
</tr>
<tr>
<td>p0</td>
</tr>
<tr>
<td>p1</td>
</tr>
<tr>
<td>p2</td>
</tr>
<tr>
<td>p3</td>
</tr>
<tr>
<td>p4</td>
</tr>
</tbody>
</table>

SF$_6$ 152torr

E = 1047 V/cm
Anode = 670V
$\Delta$GEM = 728V
Drift Velocity of SF\textsubscript{6}^{-}

- At 76Torr, Photon feedback was observed between u-PIC and GEM.

- Drift velocity \( \sim 10^{-2} \text{ cm/\mu s} \)

\[ \text{wave form} \]

\[ \text{SF6 76Torr} \]

\[ \text{E/P[v(cm*torr)]} \]
5. Summary

• A first test of $\mu$-PIC+GEM with negative ion gas was performed.
• For CS$_2$, the total gas gain is higher than 10000.
• For SF$_6$, the total gas gain is about 300.
• SF$_6$ gas needs optimization, going to study
• In the future, with both of them, minority peaks will be observed.

**MPGDs with negative ion gas will create more opportunities for low background experiment.**
Thank you for your attention!
4. Back-up
Electronics for CS$_2$

- We used CREMAT’s CR-111 charge sensitive preamplifier.

![Figure 1](image)

**Specifications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CR-111</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamplication channels</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Equivalent noise charge (ENC)*</td>
<td>630</td>
<td>electrons</td>
</tr>
<tr>
<td>ENC RMS</td>
<td>0.1</td>
<td>femtoCoul.</td>
</tr>
<tr>
<td>Equivalent noise in silicon</td>
<td>6</td>
<td>keV (FWHM)</td>
</tr>
<tr>
<td>ENC slope</td>
<td>3.7</td>
<td>elec. RMS / pF</td>
</tr>
<tr>
<td>Gain</td>
<td>0.13</td>
<td>volts / pC</td>
</tr>
<tr>
<td>6.2 mV / MeV(Si)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rise time **</td>
<td>3</td>
<td>ns</td>
</tr>
<tr>
<td>Decay time constant</td>
<td>150</td>
<td>μs</td>
</tr>
<tr>
<td>Unsaturated output swing</td>
<td>-3 to +3</td>
<td>volts</td>
</tr>
<tr>
<td>Maximum charge detectable per event</td>
<td>1.3 x10$^8$</td>
<td>electrons</td>
</tr>
<tr>
<td>Power supply voltage (V$_{+}$)</td>
<td>7.5</td>
<td>mA</td>
</tr>
<tr>
<td>maximum</td>
<td>7.5</td>
<td>mA</td>
</tr>
<tr>
<td>minimum</td>
<td>3.5</td>
<td>mA</td>
</tr>
<tr>
<td>Power supply current (pos) (neg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power dissipation</td>
<td>70***</td>
<td>mW</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-40 to +85 °C</td>
<td></td>
</tr>
<tr>
<td>Output offset</td>
<td>+0.2 to -0.2</td>
<td>volts</td>
</tr>
<tr>
<td>Output impedance</td>
<td>50</td>
<td>ohms</td>
</tr>
</tbody>
</table>

**CS2 76Torr 55Fe**

CH2 (anode 13cstrips sum) 20mV/div
CH4 (cathode 13cstrips sum) 30mV/div

VDRIFT=-1.5kV
GEM=-800V/-460V
uiPC anode=550V

**Figure 2**

![Figure 2](image)
Electronics for SF$_6$

Amplifier 1.1 V/pC 120 nC/pC

$$\chi^2 / \text{ndf} = 145.2 / 10$$
Prob = 3.674e-26
$$p_0 = 0.673 \pm 0.01421$$
$$p_1 = 1087 \pm 8.157$$
Spin dependent (SD) cross section

- The SD cross section is written using $\sigma_{SD}$ as

$$\sigma_{SD}^{\chi-N} = \sigma_{SD}^{\chi-p} \frac{\mu_{\chi-N}^2}{\mu_{\chi-p}^2} \frac{\chi^2 J(J + 1)}{0.75}.$$ 

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$J$</th>
<th>Abundance(%)</th>
<th>$\mu_{mag}$</th>
<th>$\chi^2 J(J + 1)$</th>
<th>Unpaired nucleon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>1/2</td>
<td>100</td>
<td>2.793</td>
<td>0.750</td>
<td>proton</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>3/2</td>
<td>92.5</td>
<td>3.256</td>
<td>0.244</td>
<td>proton</td>
</tr>
<tr>
<td>$^{11}\text{B}$</td>
<td>3/2</td>
<td>80.1</td>
<td>2.689</td>
<td>0.112</td>
<td>proton</td>
</tr>
<tr>
<td>$^{15}\text{N}$</td>
<td>1/2</td>
<td>0.4</td>
<td>$-0.283$</td>
<td>0.087</td>
<td>proton</td>
</tr>
<tr>
<td>$^{19}\text{F}$</td>
<td>1/2</td>
<td>100</td>
<td>2.629</td>
<td>0.647</td>
<td>proton</td>
</tr>
<tr>
<td>$^{23}\text{Na}$</td>
<td>3/2</td>
<td>100</td>
<td>2.218</td>
<td>0.041</td>
<td>proton</td>
</tr>
<tr>
<td>$^{127}\text{I}$</td>
<td>5/2</td>
<td>100</td>
<td>2.813</td>
<td>0.007</td>
<td>proton</td>
</tr>
<tr>
<td>$^{133}\text{Cs}$</td>
<td>7/2</td>
<td>100</td>
<td>2.582</td>
<td>0.052</td>
<td>proton</td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td>1/2</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$-2.128$</td>
<td>0.928</td>
<td>neutron</td>
</tr>
<tr>
<td>$^{17}\text{O}$</td>
<td>5/2</td>
<td>0.0</td>
<td>$-1.890$</td>
<td>0.342</td>
<td>neutron</td>
</tr>
<tr>
<td>$^{29}\text{Si}$</td>
<td>1/2</td>
<td>4.7</td>
<td>$-0.555$</td>
<td>0.063</td>
<td>neutron</td>
</tr>
<tr>
<td>$^{73}\text{Ge}$</td>
<td>9/2</td>
<td>7.8</td>
<td>$-0.879$</td>
<td>0.065</td>
<td>neutron</td>
</tr>
<tr>
<td>$^{129}\text{Xe}$</td>
<td>1/2</td>
<td>26.4</td>
<td>$-0.778$</td>
<td>0.124</td>
<td>neutron</td>
</tr>
<tr>
<td>$^{131}\text{Xe}$</td>
<td>3/2</td>
<td>21.2</td>
<td>0.692</td>
<td>0.055</td>
<td>neutron</td>
</tr>
<tr>
<td>$^{183}\text{W}$</td>
<td>1/2</td>
<td>14.3</td>
<td>0.118</td>
<td>0.003</td>
<td>neutron</td>
</tr>
</tbody>
</table>
Minority Peak of SF$_6$

20 Torr SF$_6$

Fiducialization?

9 % faster than larger peak

SF$_{-5}$?

2.6 %

ΔT

From N. Phan, Cygnus 2015
Amplifier for liquid Argon TPC

- Development of LTARS ASIC
  - pre-amp. & shapers in a chip
  - high density (32ch in a chip)
  - power supply voltage ±0.9V
  - ENC ~2000@300pF
  - conv. gain ~9V/pC

LTARS2014 ASIC chip (5mm x 5mm)

(developed with KEK e-sys group, one of Open-it projects http://openit.kek.jp/project/LTARS2014/LTARS2014)
Detection efficiency in detector coordinate

![Diagram showing detection efficiency in detector coordinate](image_url)