NEWAGE / CYGNUS strategy

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Contents
Dark Matter Direct detection
Physics Experiments
飛跡長と拡散

200μm/\sqrt{cm} \rightarrow 1.2mm@40cm
NEWAGE strategy since its new ages

size

diffusion

gas study

Radon

γammamas

z-fiducialization

quenching

stability

position resolution

energy resolution

energy threshold

head-tail

angular resolution

exclusion limit

neutrons

skymap

DIRECTIONALITY

DRIFT

BG

NEWAGE
NEWAGE: always direction-sensitive

- New general WIMP search with an Advanced Gaseous tracker Experiment
  - $\mu$-PIC(MPGD) based TPC
  - 3-D tracks SKYMAP
  - CF$_4$ gas for SD search

- Proposal  PLB 578 (2004) 241
- First direction-sensitive limits
  - PLB654 (2007) 58
- Underground results
- Phase for “low BG detector”
DRIFT is direction sensitive?

Yes, but not direction-sensitive analysis.
DRIFTの”direction sensitive”は？

- x 2mm y 2mm <- VETO以外には使い物にならん
- z (drift方向)の時間発展のみ使用可能 だが解析では不使用
DRIFTの"direction sensitive"は？
- z (drift方向)の時間発展のみ使用可能
- 右から来たか左から来たか 1000発あれば 統計的に識別可能

First measurement of the head–tail directional nuclear recoil signature at energies relevant to WIMP dark matter searches


Astroparticle Physics 31 (2009) 261–266
DRIFT
- best limit with directional detector

NEWAGE
- best limit with directional analysis
minority peaks “discovery” by DRIFT group
First with CS$_2$, then with SF$_6$

minority peaks (DRIFT group)

20 Torr SF$_6$ waveforms

NEWAGE SF₆ study (池田)

- SF₆ study for GEM+μPIC system
- Wide dynamic-range ASIC development

SF6 study (NEWAGE)  SF6 study (NEWAGE)

ここまでは後追い
Electronics

- Using analog and digital board made by KEK for Liquid Argon detector

**Analog Board (64ch RO)**
- cathode 32ch (ID109~140)
- anode 32ch (ID109~140)
- trigger (cathode ID107, 108)

**Digital Board (64ch RO)**
- Ethernet
- PC

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**LTARS2014**

Conversion gain: $\sim9.0\text{mV/fC}$
Max input charge: $60\sim100\text{fC}$
ENC: below 2000@300pF
Shaping time: 1us

**32ch differential inputs (2Vpp)**
- 12bits FADC
- 4000 sampling
- Sampling frequency <20MHz

2016/12/01
こういうものが他グループはできない。
NEWAGEのつよみ
方向感度に注力しながら全部やってきた。
自前のエレキがあるのが強み。
増幅できても飛跡が取れない人が多い。

lowBGはこれからだが、必要なものは全部持っている。

大型化・低BG・方向感度のバランスを取りながら、進めてゆく。
Neil Spooner: すぐにでもみんなで協力してかいもの=24m³を作ろう

Miuchi (NEWAGE): お友達はOK。国際協力はそれぞれがもっと強くなってから

戦略：CYGNUSとNEWAGEの並走

MPGDのR&Dを個別に行っている
CYGNUS(DRIFT)メンバーを連れ込むためのチェンバーを製作中。

「40cm角のモジュールをはめることができますよ」。

一部はμ-PIC(NEWAGE)を優先的に配置。
→ NEWAGEの名前、アクティビティーはキープ

既成事実からの協力を期す

SKは50000m³ → 5tくらいのガスになる
まとめ

- 方向に感度をもった発見、暗黒物質の銀河内での運動、反応を目指す。

- 必要に応じて国際協力も
“CYGNUS” concept

Direction-sensitive dark matter search even below the “neutrino floor”
Clear detection of dark matter DM precise study after detection DM kinematics in the galaxy, DM–nucleon interaction operators…
Difficulty: short track (a few mm > )

Gas TPC
DRIFT
NEWAGE MIMAC
DM–TPC
D3 NITEC

Solid/Liquid
NEWS DCaNT
ZnWO4 RED

seasonal modulation

Expected $\cos \theta$ distribution

$M=80\text{GeV}$
$\sigma=0.1\text{pb}$

Counts/3m$^3$/year/bin

$\cos \theta$
DAMA

NaI 250kg
14サイクルの「季節変動」
新しい結果は来年出す。

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1
Total exposure: 487526 kg×day = 1.33 ton×yr

Continuous line: $N = 152.5 \text{ d}, T = 1.0 \text{ y}
A = (0.0110 \pm 0.0012) \text{ cpd/kg/keV}
$\chi^2$/dof = 70.4/86  9.2 $\sigma$ C.L.

Absence of modulation? No
$\chi^2$/dof = 154/87 $P(A=0) = 1.3 \times 10^{-5}$

Fit with all the parameters free:
$\Delta A = (0.0110 \pm 0.0012) \text{ cpd/kg/keV}$

DAMA/LIBRA phase 2 - running

The data favor the presence of a modulated behaviour with features for DM particles in the galactic halo at about $\alpha/E = 59.5$ keV for each detector with new PMTs with higher quantum efficiency (blue points) and with previous PMT-EMI-Electron Tube (red points).

The light responses
- Previous PMTs: 5.5-7.5 ph.e./keV
- New PMTs: up to 10 ph.e./keV
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for other rare processes
**NEWAGE detector**

- **NEWAGE-0.3b’**
- Detection Volume: $31 \times 31 \times 41 \text{cm}^3$
- Gas: CF4 at 0.1atm (50keVee threshold)
- Gas circulation system with cooled charcoal
NEWAGE-0.3b’ inside view

Detection Volume: $30 \times 30 \times 41 \text{cm}^3$

Field cage
- Drift length: 41cm
- PEEK + copper wires

μ-PIC (Micro-pixel chamber)
- $31 \times 31 \text{cm}^2$
- pitch: 400μm
- gain: ~1000
- made by DNP, Japan

GEM
- $31 \times 32 \text{ cm}^2$
- 8-segmented
- hole pitch: 140μm
- hole diameter: 70μm
- insulator: LCP 100μm
- gain: ~5
- made by Scienergy, Japan
NEWAGE-0.3b’ readouts

- $\mu$-PIC is X-Y readout
- ALTAS TGC ADS chips
- General purpose FPGA-based electronics since early 2000’s
NEWAGE-0.3b’ data

- TOT of every strip by FPGA (clock 100MHz)
  \[ \Rightarrow \] 3D tracks, headtails in X,Y

- Summed waveforms by FADC (100MHz)
  \[ \Rightarrow \] energy, headtails in Z

Combined \[ \Rightarrow \] PID, absolute z
NEWAGE-0.3b' performance

- Nuclear track detection efficiency: 40% @ 50 keVee
- Gamma rejection: 2.5e-5 @ 50 keVee
- Energy resolution: 7.8 keV $\sigma$ @ 50 keVee
- Angular resolution: 40° $\sigma$ @ 50 keVee

Nuclear track detection efficiency

Electron track detection efficiency (gamma rejection factor)
NEWAGE in KAMIOKA

Kamioka Underground site

B01/C02: XMASS

A01/C02: KamLAND

D01: Low-radioactivity R&D (LAB-A, 2015~)

A02: CANDLES

C02: Super-Kamiokande

C01: SK-Gd water system

IPMU

Rn det. (D01)

APIMS

GC

Ge det. ...

Atotsu Entrance (~2km)

C01: R&D of SK-Gd

B02: NEWAGE

Superconductive gravimeter

CLIO (Gravitational wave exp.)

Laser extensometer (Geophysics)

http://www-sk.icrr.u-tokyo.ac.jp/
NEWAGE underground run

RUN14
• period: 2013/7/20-8/11, 10/19-11/12
• live time: 31.6 days
• fiducial volume: 28x24x41cm³
• mass: 10.36g
• exposure: 0.327 kg·days

**Energy spectrum**
• Threshold: 100 => 50keV
• BG rate: 1/10@100keV

**Skymap, cosθ distribution**
• Set limit by significant difference in 2-binned measured cosθ and DM-wind simulated cosθ
 Galactic-plane sky-map

- correlation with efficiency = consistent with isotropic

lab-coordinate

galactic coordinate

Energy 50-100keV
• Obtained limit: **557pb @200GeV**
  (Best direction-sensitive limit)
• Improved one order of magnitude from previous RUN5

**PTEP (2015) 043F01s**
Recent R&Ds
Dark Matter exists in many scales of the universe.

@ Galaxy: Rotation Curves (1970~)

@ Clusters of Galaxies: clusters of galaxies’s collision (2007~)

@ Universe: CMB and other obsevations (2002~)
Attack the Dark Matter

Accelerator experiment
MAKE it!

Indirect Search
SEE it!

Direct Search
WAIT for it!
Dark Matter Direct Searches (2016)

- \( E_R(\text{photon}) \)
  - DAMA, DM-ICE
  - COSINE, SABRE, ANAIS (NaI)
  - KIMS (CsI, NaI)
  - DEAP
  - XMASS (Xe)

- \( E_R(\text{charge}) \)
  - XENON, LUX, PANDA-X, LZ (Xe)
  - DarkSide (Ar)

- \( E_R(\text{heat}) \)
  - CRESST (CaWO4)
  - PI-COUPP, SIMPLE (CxFx)

- \( E_R(\text{photon} + \text{charge}) \)
  - CoGent
  - DAMIC (Ge)
  - NEWS-SNO (Ne)

- \( (\text{photon} + \text{heat}) \)
  - CDMS (Ge/Si)
  - EDELWEISS (Ge)

- \( (\text{charge} + \text{heat}) \)
  - DRIFT, NEWAGE, DMTPC, MIMAC, NEWS (elustion)
2-phase Xenon detectors

- 2-phase Xenon: XENON (161 kg total)
- Good gamma rejection

LUX (250 kg active) PandaX-II (500 kg sensitive)

**PandaX-II**

- New stainless steel vessel with lower radioactivity
- 55 R11410 (top)
- 48 R8520 (veto)
- Teflon with better reflectivity
- Electrode rings fully covered by Teflon
- 55 R11410 (bottom)
- Overflow chamber inside the vessel

**LUX detector**

- 48 cm diameter by 48 cm height dodecagonal “cylinder”.
- 250.9 kg LXe in active region
- 61 PMTs on top, 61 on bottom, specially produced for low radiogenic BGs and VUV sensitivity.
- Xenon was pre-purified via chromatographic separation, reducing residual krypton.
- Liquid is continuously recirculated (½ tonne per day) to maintain chemical purity.
- Ultra-low radiative Bg titanium cryostat.

- Improved base design

- New separate skin veto region
DAMA and others…
in tension

any other clear evidence?

directionality!
BG study

Directionality helps!

SKYMAP @ detector coordinate
lower energy
radon peak
color: number of events

BG identified: upgoing events
Low BG R&Ds

- Largest BG source: alpha particle from $\mu$-PIC
- Development of radio-pure ($BG \times 1/100$) $\mu$-PIC: $10 \times 10 \text{cm}^2$ $\mu$-PIC was made and tested

FY2016: development of $30 \times 30 \text{cm}^2$ $\mu$-PIC
FY2017+: underground run
MICROMEGAS and Multi GEM

- \( \mu \)-PIC(+GEM)
  - Anode diameter: 50um
  - Cathode hole diameter: 250um
  - Made by DNP in Japan

- Multi GEM
  - Width: 100um
  - Material: liquid crystal polymer
  - Made by Scienergy in Japan
  - \( \mu \)-PIC+GEM system, we don’t know only GEM gain.
  - How gain can we get?

MICROMEGAS

- Pillar length: 125um
- Strip pitch: 400um
- Made by Raytech in Japan
- Can we use Micro Megas in SF\(_6\) gas?
“CYGNUS” physics after discovery

Test the interaction by scattering angle

\[ \mathcal{O}_1 = 1 \]
\[ \mathcal{O}_3 = i \mathbf{S}_n \cdot \left( \frac{\mathbf{q}}{m_n} \times \mathbf{v}^\perp \right) \]
\[ \mathcal{O}_4 = \mathbf{S}_X \cdot \mathbf{S}_n \]
\[ \mathcal{O}_5 = i \mathbf{S}_X \cdot \left( \frac{\mathbf{q}}{m_n} \times \mathbf{v}^\perp \right) \]
\[ \mathcal{O}_6 = (\mathbf{S}_X \cdot \mathbf{q})(\mathbf{S}_n \cdot \mathbf{q}) \]
\[ \mathcal{O}_7 = \mathbf{S}_n \cdot \mathbf{v}^\perp \]
\[ \mathcal{O}_8 = \mathbf{S}_X \cdot \mathbf{v}^\perp \]
\[ \mathcal{O}_9 = i \mathbf{S}_X \cdot (\mathbf{S}_n \times \mathbf{q}) \]
\[ \mathcal{O}_{10} = i \mathbf{S}_n \cdot \mathbf{q} \]
\[ \mathcal{O}_{11} = i \mathbf{S}_X \cdot \mathbf{q} \]
\[ \mathcal{O}_{12} = \mathbf{S}_X \cdot (\mathbf{S}_n \times \mathbf{v}^\perp) \]
\[ \mathcal{O}_{13} = i (\mathbf{S}_X \cdot \mathbf{v}^\perp) \left( \frac{\mathbf{S}_n \cdot \mathbf{q}}{m_n} \right) \]
\[ \mathcal{O}_{14} = i \left( \frac{\mathbf{S}_X \cdot \mathbf{q}}{m_n} \right) (\mathbf{S}_n \cdot \mathbf{v}^\perp) \]
\[ \mathcal{O}_{15} = - \left( \frac{\mathbf{S}_X \cdot \mathbf{q}}{m_n} \right) \left( \mathbf{S}_n \times \mathbf{v}^\perp \right) \cdot \left( \frac{\mathbf{q}}{m_n} \right). \]
"CYGNUS" physics after discovery

Test the interaction by scattering angle

$$\frac{dR}{d\cos\theta}$$

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<td>170</td>
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<td>180</td>
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</table>

Proportional to

$$\begin{align*}
1 &= \mathcal{O}_1, \mathcal{O}_4, \\
v_1^2 &= \mathcal{O}_5, \mathcal{O}_7, \mathcal{O}_8, \\
q^2 &= \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_{11}, \mathcal{O}_{12}, \\
v_1^2q^2 &= \mathcal{O}_{13}, \mathcal{O}_{14}, \\
q^4 &= \mathcal{O}_6, \\
q^2(q^2 + v_1^2) &= \mathcal{O}_{15}, \\
q^{-4} &= \mathcal{O}_{1}^{LR}.
\end{align*}$$

$$\mathcal{O}_1 = 1$$

$$\mathcal{O}_3 = i \bar{S}_n \cdot \left( \frac{\bar{q}}{m_n} \times \bar{v} \right)$$

$$\mathcal{O}_4 = \bar{S}_X \cdot \bar{S}_n$$

$$\mathcal{O}_5 = i \bar{S}_X \cdot \left( \frac{\bar{q}}{m_n} \times \bar{v} \right)$$

$$\mathcal{O}_6 = (\bar{S}_X \cdot \bar{q})(\bar{S}_n \cdot \bar{q})$$

$$\mathcal{O}_7 = \bar{S}_n \cdot \bar{v}$$

$$\mathcal{O}_8 = \bar{S}_X \cdot \bar{v}$$

$$\mathcal{O}_9 = i \bar{S}_X \cdot (\bar{S}_n \times \bar{q})$$

$$\mathcal{O}_{10} = i \bar{S}_n \cdot \bar{q}$$

$$\mathcal{O}_{11} = i \bar{S}_X \cdot \bar{q}$$

$$\mathcal{O}_{12} = \bar{S}_X \cdot (\bar{S}_n \times \bar{v})$$

$$\mathcal{O}_{13} = i(\bar{S}_X \cdot \bar{v})(\bar{S}_n \cdot \bar{q})$$

$$\mathcal{O}_{14} = i \left( \frac{\bar{S}_X \cdot \bar{q}}{m_n} \right) (\bar{S}_n \cdot \bar{v})$$

$$\mathcal{O}_{15} = - \left( \frac{\bar{S}_X \cdot \bar{q}}{m_n} \right) \left( \bar{S}_n \times \bar{v} \right) \cdot \bar{q} \left( \frac{\bar{q}}{m_n} \right).$$
NEWAGE: 

direction sensitive with 3D track detection.

Sensitivity improvements are on-going.
backup
Latest underground data

- RUN14 (31.6 days) + 172.08 days
- gamma-ray cut improvements
- increased statistics

NEWAGE 2015 (RUN14-1,2) (live=31.62 days)
RUN14+15+16 (live=203.70 days)

Galactic coordinate system
- Color: efficiency
- Dots: recoil events
DAMA and others…
in tension

any other clear evidence?
Galactic-plane sky-map

correlation with efficiency = consistent with isotropic
3. Direction sensitive background study

RUN14 Measurement

- Fiducial-cut only and high energy events (500~15000 keV)
- The directional distribution is not isotropic
- Mary vertical events
Simulated and measured TOT-sum are alike
Background events are considered to be due to α-particles
We can divide into two regions by the red line

- We records Time-Over-Threshold (TOT)
- TOT is the time duration of waveform
- TOT-sum is a sum of the TOT of all strip
In the upper region

- Isotropic distribution
- Peak component

the measurement is Consistent with the simulation
Continuous component

In the bottom region
- Mary vertical events
- Continuous component

$^{238}\text{U}$ in $\mu$-PIC (substrate)
Direction of vertical events

We can obtain measured elevation angle distribution as "normal Bragg curve" regardless of α energy.

- α energy > ~4MeV: "Normal Bragg curve"
- α energy < ~1MeV: "Inversed Bragg curve"

We consider the energy deposition of α particles as a function. This function has a peak around 1MeV:
- α energy > ~4MeV: "Normal Bragg curve"
- α energy < ~1MeV: "Inversed Bragg curve"

α-particles are in the +Z direction.

• We can obtain measured elevation angle distribution as "normal Bragg curve" regardless of α energy.
  - > ~4MeV: ±Z → ±Z
  - < ~1MeV: ±Z → ±Z
Origin of +Z direction

- The α background source should be located in μ-PIC or GEM(5,5′,6,6′,7,7′)
- We simulated the α particles emission from Th-chain in each parts
Origin of +Z direction

The result is consistent with HPGe + simulation study.

α particles emission from Th-chain in μ-PIC reproduce RUN14 measurement.
Figure 4.4.18: $|\cos \theta|$ distribution of the scattering angle in nuclear recoil events that occur by irradiation with neutrons from $^{252}$Cf. The energy range of left, center, and right figures are $50 - 100$ keV, $100 - 200$ keV, and $200 - 400$ keV, respectively. Measured and simulated distributions are shown by blue and green histograms respectively.

Figure 4.4.21: Obtained angular resolution for each energy.
Cut improvement

\textit{TOT(Time Over Threshold)-sum-cut} (gamma-ray cut)

- Nuclear ($^{252}\text{Cf}$): TOT-sum is proportional to energy
- Electron ($^{137}\text{Cs}$): scratched track (small dE/dx)

\begin{itemize}
  \item Nuclear ($^{252}\text{Cf}$): TOT-sum is proportional to energy
  \item Electron ($^{137}\text{Cs}$): scratched track (small dE/dx)
\end{itemize}
Head/tail study

- Head tail in X-Y plane, Z-axis
- Proof of concept, DONE.
- Improvement for practical use: being studied

X-Y plane

Z axis

Skewness

Proof of concept, DONE.
NEWAGE and CYGNUS

half-NEWAGE half-CYGNUS “observatory”

1m

HV X-ray tube

1m

1m

1m

triple GEM
(5 × 30 × 30cm²)

μPIC+GEM
(4 × 30 × 30cm²)

SF₆ 50Torr

DRIFT Plane

triple GEM
(can be replaced by request)
(9 × 30 × 30cm²)

NEWAGE-0.6a

0.36 m³ × 70% × 2 years × 300g/m³ > 50kg days

CYGNUS-KM1a

1.26 m³ × 85% × 2 years × 300g/m³ > 200 kg days
1500ch feedthrough

- feedthrough board
- everything is out of the vessel
- easy to maintain
- keep the gas purity
NEWAGE-0.3b’ performance

- Energy threshold: 50keV
- Energy resolution: 20% (dominated by gain non-uniformity)
- Nuclear track detection efficiency: 40% @50keVee
- Gamma rejection 2.5E-5@50keVee
- Angular resolution 40° @50keVee
NEWAGE-0.3b’ : calibration

- α’s from $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction
- $^{10}\text{B}$ plate stays in the TCP
- irradiated with thermalized neutrons

Linearity check: 1.5MeV+ 5.9keV, 6MeV
Event selection 1

**length-cut** (conventional gamma-ray cut)

dE/dx: nuclear ($^{252}$Cf) > electron ($^{137}$Cs)
track length: electron > nuclear
Event selection 2

**TOT-sum-cut** (new gamma-ray cut)

- Nuclear \((^{252}\text{Cf})\): TOT-sum is proportional to energy
- Electron \((^{137}\text{Cs})\): scratched track (small dE/dx)
**Event selection 3**

**roundness-cut (third cut)**

Remained $^{137}$Cs events: **straight** track shape

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**Diffusion** (drift distance) affects roundness!  
(April all electron events are cut)  
(Remained events are BG $\alpha$ from $\mu$-PIC)  
Roundness-cut works as “z-fiducial-cut”
After all cut, compare to Geant4

- **Nuclear (\(^{252}\text{Cf}\) neutron source)**
  Efficiency: \(40\%\)@50keV

- **Electron (\(^{137}\text{Cs}\) γ source)**
  Rejection: \(2.5 \times 10^{-5}\)@50-100keV
Galactic-plane sky-map

Demonstration for direction sensitivity

Detector Coordinate

Lab frame

N
E
S
W

Z
W
S
E
N

latitude
elevation

galactic latitude
galactic longitude
declination
right ascension

equatorial coordinate
equatorial coordinate

Galactic Centre

The Sun

Direction of North Galactic Pole

Direction of South Galactic Pole

Direction of Galactic Anti-centre

star

celestial sphere

celestial equator

terrestrial sphere

Equator

tropical equinox

North celestial pole

South celestial pole