First limits from a 3d-vector directional dark matter search with the NEWAGE-0.3b’ detector

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1. Introduction

A considerable number of cosmological observations show strong evidence that an unknown particle, so called dark matter, constitutes about 27% of the universe[1]. Weakly interacting massive particles (WIMPs) are considered to be one of the best dark matter candidates and direct detection experiments have sought for the evidence of the elastic scattering between a WIMP and a nucleus. With a natural assumption that dark matter WIMPs are trapped gravitationally in galaxies, the solar system should receive a dark matter wind due to the rotation about the center of Milky Way. Detecting the direction of nuclear recoil has been said to be a reliable detection method for positive WIMP signatures[2, 3]. Furthermore, it is said that this method would be a strong tool in the search for WIMPs even below the so-called neutrino floor at which neutrino-nucleus coherent scatterings take place[4]. Gaseous time projection chambers (TPC) can detect the directions of nuclear recoil tracks and several types of TPCs with charge and optical readout have been developed and dark matter searches were carried out[5–7].

NEWAGE is a directional direct dark matter search experiment using a three-dimensional gaseous tracking detector, or a micro time projection chamber (µ-TPC). The latest directional WIMP-proton cross-section limits by NEWAGE reported in Ref.[6] came as the result of about 30 days of measurement. We continued the measurement keeping the same detector condition and increased the statistics more than 10 times. We also improved the analysis so that the head-tail asymmetry parameters of the nuclear tracks can statistically be known.
In this paper, recent results of the NEWAGE experiment with aforementioned updates are described. The detector system and its performance including the event selection are described in Section 2. In Section 3, the measurement properties and results of a directional dark matter search are described. Future prospects are discussed in Section 4 and the paper is concluded in Section 5.

2. Detector

2.1. NEWAGE-0.3b’ overview

One of the NEWAGE detectors, NEWAGE-0.3b’, was used for this directional WIMP search. NEWAGE-0.3b’ consists of a micro time projection chamber (µ-TPC), a gas circulation system, and an readout electronics system. Schematics of the µ-TPC and its internal structure are shown in Fig. 1. The µ-TPC consists of a two-dimensional imaging device known as a micro pixel chamber (µ-PIC) [8], a gas electron multiplier (GEM) [9], and a drift cage. The detection volume is \(30.7 \times 30.7 \times 41.0\) cm\(^3\). The X and Y axes are defined to be parallel to the µ-PIC readout strips and the Z-axis is defined to be parallel to the drift direction. The origin of the axis is set at the center of the detection volume. The detection volume was filled with CF\(_4\) gas at 76 torr. CF\(_4\) gas was selected as the target gas because the gas diffusion is small and fluorine has a relatively large spin-dependent (SD) cross section for WIMPs.

Fig. 1: Schematic view of the µ-TPC. The µ-TPC consists of a µ-PIC, a GEM, and a drift cage. The detection volume is \(30.7 \times 30.7 \times 41.0\) cm\(^3\).

A µ-PIC (Dai Nippon Printing Co., Ltd.) is a variation of the micro-patterned gaseous detectors and is manufactured using printed circuit board (PCB) technology[8]. The PCB technology can produce a large-sized detector at a reasonable cost, which is one of the most important requirements of the technological choice for a gas chamber readout for WIMPs. The effective area of the µ-PIC for the NEWAGE-0.3b’ was \(30.7 \times 30.7\) cm\(^2\) read by two-dimensional strips with a pitch of 400 \(\mu\)m in both the X and Y directions. Because of the structure of the electrodes, these two-dimensional strips are referred to as anode (x) and
cathode (y) strips, respectively. Hereafter, the strip IDs are represented by x and y, whereas the positions in real geometry are expressed by X and Y in units of centimeters. Positive bias was applied to the anode electrodes which are in a shape of pixels with an outer diameter of 70 µm. Gas amplifications take places around the anode electrodes. Ions drift towards the cathode electrodes which have a circular shape of inner diameter 260 µm. Same amount of positive and negative charges were read through the anode and cathode strips. A GEM, manufactured by SciEnergy., Ltd., was placed 4 mm above the µ-PIC as a sub-amplifier to ensure gas gain while reducing the risk of the discharges. The effective area of the GEM (31 × 32 cm²) covered the entire detection area of the µ-PIC. The GEM was made of a 100 µm-thick liquid crystal polymer and the hole size and pitch were 70 µm and 140 µm, respectively. The drift length was 41.0 cm. The electric field was formed by a drift plane and 1 cm-spaced wires on side walls made of polyetheretherketone. A glass plate with a thin layer of ¹⁰B was installed at a position of (−5.0, −12.0, 0.0) for energy calibration. The size of the ¹⁰B layer was 2.0 × 2.0 cm² with a thickness of 0.6 µm. The µ-TPC was placed in a stainless-steel vacuum vessel.

A gas circulation system with cooled charcoal was installed to reduce radon, which is a major source of background for WIMP searches, and to maintain the gas quality during long measurements. The gas in the vessel passed through the filter where 100 g of charcoal (TSURUMICOAL 2GS) absorbed the radon and other impurities. The gas was circulated at a rate of 500 ~ 1000 mL/min using a dry pump (XDS5 Scroll Pump, EDWARDS). Stable cooling at 230 K ±2 % was realized by controlling a heater, whereas the cooler (CT-910 Cool Man Trap (SIBATA)) was always operated at its maximum cooling power. The detector stability will be discussed in Section 3.2.

A data acquisition (DAQ) system dedicated to the µ-PIC readout was used for the measurement. Details are described in Ref. [6]. The DAQ system recorded two types of data, “charges” by a flash-ADC (FADC) and “tracks” by a memory board. Analog signals from 768 cathode electrodes were grouped down to 4 channels and their waveforms were recorded with a 100 MHz FADC as the charge data. TPC analog signals from 768 anode strips were grouped down to 16 channels and a hit at any one of them was used as a trigger. The rising and falling edge timings (t) of each strip were recorded as the track data. In this DAQ system, the absolute z position was not measured since the trigger was issues at a timing of the arrival of the first hit on the µ-PIC. A typical nuclear track sample taken with this DAQ system is shown in Fig. 2.

2.2. Event parameters

Several parameters were defined to characterize the track property of each event. Waveforms recorded by the FADC were used to know the charge of each event, which in turn were converted into energy (E) with a calibration factor. Energy calibration was carried out with α particles using the ¹⁰B(n, α)⁷Li reaction by irradiating the ¹⁰B plate with thermal neutrons as described in our previous paper[6]. The energy scale calibrated by α particles was used for further discussion.

Event parameters on the track information will be explained using an event display shown in Fig. 2. The upper panels ((a),(b)) show the recorded raw data on the anode (x) and cathode (y) strips, respectively. The rising edge (shown with blue marker) and the falling
Fig. 2: A typical event display for a measurement with a $^{252}$Cf neutron source. The top-left (a) and top-right (b) panels show raw track data on the $x - t$ and $y - t$ panels, respectively. Blue and black markers show the rising and falling edges, respectively. Red markers show the durations of the signals. Green lines show the fitted track. The bottom-left (c) and bottom-right (d) panels show time-over-threshold (TOT) distributions along the $X$ and $Y$ axes, respectively. Details are described in Sections 2.1 and 2.2.

edge (shown with black marker) of each strip are recorded and the time-over-threshold (TOT) of each strip is determined as the difference between the clocks of these edges. The rising edges represented the arrival time of drifting electrons on each strip. The relative times of rising edges to the trigger timing thus represented the $Z$ positions within a track. The TOT of each strip corresponded to the energy deposition therein. The TOTs of strip IDs $x$ and $y$ were defined as $TOT(x)$ and $TOT(y)$, respectively. The TOT-sum of the $x$ strips ($TS_x$) and $y$ strips ($TS_y$) were defined as Eqs. (1) and (2).

$$TS_x \equiv \sum_{x=x_{\text{min}}}^{x_{\text{max}}} TOT(x)$$  \hspace{1cm} (1) \hspace{1cm} $$TS_y \equiv \sum_{y=y_{\text{min}}}^{y_{\text{max}}} TOT(y)$$  \hspace{1cm} (2)$$

Here min and max represent the minimum and maximum IDs of the hit strips on the corresponding coordinate.

The lower panels ((c),(d)) of Fig. 2 show the TOTs with rising edges shifted to zero for a better view of the TOT distributions along the axes. To parameterize the asymmetry of the TOT distribution, or the energy deposition, along the $x$ and $y$ coordinates, a parameter
named skewness was defined. Here the energy deposition distribution had some information about the track sense along each axis. The tracks of the corresponding energy were known to have larger energy depositions at the start than at the end. In the event shown in Fig. 2, the track ran from left to right on the $X$ axis, whereas no clear difference was not seen along the $Y$ axis. Skewnesses ($SK_x$ and $SK_y$) for the $x$ and $y$ strips are defined by Eqs. (3) - (8).

\[
SK_x = \frac{S_{3x}}{S_{2x}^{3/2}}, \quad (3)
\]

\[
S_{nx} = \sum_{x=x_{\text{min}}}^{x_{\text{max}}} \frac{(x-<x>)n \cdot \text{TOT}(x)}{TS_x}, \quad (4)
\]

\[
<x> = \sum_{x=x_{\text{min}}}^{x_{\text{max}}} \frac{x \cdot \text{TOT}(x)}{TS_x}, \quad (5)
\]

\[
SK_y = \frac{S_{3y}}{S_{2y}^{3/2}}, \quad (6)
\]

\[
S_{ny} = \sum_{y=y_{\text{min}}}^{y_{\text{max}}} \frac{(y-<y>)n \cdot \text{TOT}(y)}{TS_y}, \quad (7)
\]

\[
<y> = \sum_{y=y_{\text{min}}}^{y_{\text{max}}} \frac{y \cdot \text{TOT}(y)}{TS_y}. \quad (8)
\]

Until now, the parameters in the $x - t$ and $y - t$ planes has been used for the discussion, where $t$ is defined in units of time. Through the knowledge of the drift speed, $t$ can be converted into $Z$ which has units of length. Hereafter, the parameters are defined in the $X - Z$ and $Y - Z$ planes with conversions into $X$ and $Y$ units. To characterize the track shapes, the rising edges in the $X - Z$ and $Y - Z$ planes were fitted with lines (green lines in Fig. 2). Here the slopes of the best-fit lines in the $X - Z$ and $Y - Z$ planes are parameterized as $m_X$ and $m_Y$, respectively. The $Z$-axes sections are defined as $n_X$ and $n_Y$.

The length of the best-fit line between the min and max strip ID was calculated on each plane. $\Delta X$ and $\Delta Y$ were taken from these lines and the smaller of the two $\Delta Z$s were taken as the $\Delta Z$. The length in the 3D space ($L$) was calculated by the square root value of the sum of squares ($L = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}$).

The roundness parameter ($R$), which represents the shape of the tracks, was defined by Eq. (11).

\[
R_X = \sum_{x=x_{\text{min}}}^{x_{\text{max}}} \frac{(Z_{\text{rise}}(X) - m_X X - n_X)^2}{X_{\text{max}} - X_{\text{min}}}, \quad (9)
\]

\[
R_Y = \sum_{y=y_{\text{min}}}^{y_{\text{max}}} \frac{(Z_{\text{rise}}(Y) - m_Y Y - n_Y)^2}{Y_{\text{max}} - Y_{\text{min}}}, \quad (10)
\]

\[
R = \min(R_X, R_Y), \quad (11)
\]

where $Z_{\text{rise}}(X)$ and $Z_{\text{rise}}(Y)$ are the rising edges at $X$ and $Y$, respectively.

Because $m$ and $SK$ were found to have correlations due to the time-walk effect of the rising-edge timing, these parameters were corrected so that $m$ values would not show $SK$.
dependence in the $m - SK$ planes. The corrected skewness parameters ($cSK_X$ and $cSK_Y$) were used for further discussions. The azimuth ($\phi$) and elevation ($\theta$) of the tracks were also calculated from the corrected slope parameters ($cm_X$ and $cm_Y$).

2.3. Event Selection and Detector Performance

Several event selections were applied to reject various types of backgrounds. A fiducial area of $28.0 \times 24.0 \text{ cm}^2$ was defined and the whole track was required to be in this fiducial area. This cut (fiducial cut) mainly rejected protons and electrons from the wall of the drift cage and the $^{10}\text{B}$ plate.

The electron tracks mainly due to external $\gamma$-rays were rejected by the L and TS cuts. This rejection was realized based on the fact that the energy deposition per unit distance of an electron is much smaller than that of a nucleus. Therefore, the $L$ and $TS$ of the electrons were expected to be longer and smaller than those of the nucleus, respectively. In this work, an energy dependence was added to the TS cut to improve the rejection power.

Alpha-particle events from the $\mu$-PIC, which were a major source of backgrounds, were eliminated by the R cut. These four cuts were also used in our previous work[6]. Two additional cuts, the $\theta$ cut and the SK cut, were introduced for this work. The $\theta$ cut rejected $\alpha$-particle background going through GEM holes from the $\mu$-PIC. These tracks have large $\theta$ so a cut of large $\theta$ would discriminate these events. The SK cut was introduced to enhance the head-tail discrimination power by rejecting events with small absolute values of $SK$s. The cut criteria are listed below.

The energy dependencies of these parameters for nuclear events by $^{252}\text{Cf}$ and $\gamma$-ray events by $^{137}\text{Cs}$ at each cut stage are shown in Fig. 3. The $\theta$ distribution for the $^{252}\text{Cf}$ run after the R cut is shown in Fig. 4.

- **Fiducial cut**: $(X/\text{cm}) \leq -14$ or $14 \leq (X/\text{cm})$ or $(Y/\text{cm}) \leq -10$ or $14 \leq (Y/\text{cm})$
- **L cut**: $(L/\text{cm}) > 0.6 + 0.004 \times (E/\text{keV})$
- **TS cut**: $TS_X < 50 + 0.5 \times (E/\text{keV})$ or $TS_Y < 50 + 0.5 \times (E/\text{keV})$
- **R cut**: $R/\text{cm}^2 < 0.04$
- **$\theta$ cut**: $|\sin\theta| < 0.5$
- **SK cut**: $|cSK| < 0.1$

We then describe the detector performance specific to this analysis. The first performance is the head-tail determination power ($HP$) or the sense determination of the measured tracks. After the fundamental studies with prototype detectors [10, 11], head-tail determination was applied to NEWAGE dark matter analysis for the first time. The $HP$ was studied by irradiating the detector with neutrons from the neutron source at various positions. Comparison of the $cSK$ distribution results of irradiations with the source placed at the opposite positions provided the $HP$ results. Because a head-tail determination along at least one axis can provide a head-tail to the track, $HP$s in the $X$–$Y$ plane was studied. A comparison of the results with the source at $(-25.5, 0, 0)$ (hereafter referred to as $-X$) and $(25.5, 0, 0)$ ($+X$) was used to evaluated the $HP$ along the X axis. The data with $(0, -25.5, 0)$ ($-Y$) and $(0, 25.5, 0)$ ($+Y$) were used to evaluate the $HP$ along the Y axis. The measured
Fig. 3: Energy dependences of $L$ after the fiducial cut (top-left), $TS_X$ after the L cut (top-right), $TS_Y$ after the L cut (bottom-left), and $R$ after the TS cut (bottom-right). Red and blue points represent the results of $^{252}$Cf and $^{137}$Cs measurements, respectively.

Fig. 4: The measured $\sin \theta$ distribution with $^{252}$Cf after the R cut.
cSK distributions are shown in Fig. 5 for three energy ranges. The upper panels show the cSK_{X} distributions for +X (blue) and −X (red) data and the lower panels show the cSK_{Y} distributions for +Y (blue) and −Y (red) data. The HP for an irradiation was defined as the fraction of normalized area with the absolute values corresponding to cSK larger than 0.1. Binomial errors were assigned for the HPs. The measured HPs are summarized in Table 1. The results of +X, −X, +Y and −Y for each energy range were found to be consistent with each other within the statistical errors so the averaged values with propagated errors are going to be used in the following discussions. The obtained HPs are (53.4±0.5)% for 50-100 keV, (57.7±0.4)% for 100-200 keV and (65.1±0.5)% for 200-400 keV, respectively.

Table 1: Head-tail determination powers for 50-100 keV, 100-200 keV, 200-400 keV

| energy range   | HP_{+X} [%] | HP_{−X} [%] | HP_{+Y} [%] | HP_{−Y} [%] | average [%] |
|---------------|-------------|-------------|-------------|-------------|-------------|
| 50-100 keV    | 52.2 ± 0.8  | 55.4 ± 0.9  | 54.0 ± 0.9  | 52.0 ± 1.2  | 53.4 ± 0.5  |
| 100-200 keV   | 57.7 ± 0.7  | 57.4 ± 0.8  | 59.3 ± 0.8  | 56.5 ± 1.1  | 57.7 ± 0.4  |
| 200-400 keV   | 65.2 ± 0.8  | 63.9 ± 0.9  | 67.5 ± 0.8  | 63.6 ± 1.2  | 65.1 ± 0.5  |
| histogram in Fig. 5 | blue(top) | red(top) | blue(bottom) | red(bottom) |
The detection efficiencies of nuclear and electron events after these cuts applied were evaluated by dividing the measured energy spectrum by the simulated one. An ideal simulation result, not including the detector responses was used as the denominator. An averaged spectrum of 6 measurements by placing a $^{252}$Cf to six positions was used to cancel the position dependence and to measure the overall response of the detector. The six positions were $(25.5, 0, 0), (-25.5, 0, 0), (0, 25.5, 0), (0, -25.5, 0), (0, 0, 47.5)$ and $(0, 0, -47.5)$. Typical detection efficiencies for the nuclear recoil events after all cuts are shown in Fig. 6(left). The detection efficiency of nuclear events was found to be 9% at 50 keV. The detection efficiencies of electron events, or the gamma-ray rejection power, were evaluated by irradiating the detector with $\gamma$-rays from a $^{137}$Cs source and comparing the data with the simulation results. The obtained detection efficiency of the electron events in the energy bin 50 - 100 keV was $1.25 \times 10^{-5}$.

The directional response to an isotropic distribution of the track directions was shown in Fig. 6(right). This distribution was obtained as the sum of the distributions of six positions weight by live times and then normalized so that the mean equals 1. The measured directional response is used for weighting the expected direction distribution of recoil nuclear track in the directional dark matter search analysis with a 3d-vector tracking method.

The angular resolution of the nuclear tracks was measured using the fast neutrons from a $^{252}$Cf source. It was evaluated by comparing the measured and simulated distributions of recoil angle. The measured angular resolution results in the energy bin 50-100 keV was $(36 \pm 4)^{\circ}$[12]. The energy resolution was estimated by fitting the energy spectrum of the radon peak and the FADC waveform. The energy resolution obtained from the width of the radon peak was due to the position dependence of the gas gain and the attachment of electrons during the drift. The electric noise component in the energy resolution was evaluated with the FADC waveform data. The obtained total energy resolution was $13 \pm 1\%$ for 50 keV.

![Graphs](image.png)

Fig. 6: The detection efficiency(left) and directional response(right) of nuclear events.
3. Directional dark matter search
3.1. Measurement

A dark matter search experiment was carried out from July 2013 to August 2017 in Laboratory B, Kamioka Observatory (36°25’ N, 137°18’ E), at a water equivalent depth of 2700m. The run properties are summarized in Table 2. The "main" run number was incremented when the hardware was modified and the "sub" run number was incremented when the chamber gas was changed. The total live time used for this work was 434.85 days, corresponding to an exposure of 4.51 kg-days.

Table 2: Measured dates and live times for this work. Detector orientation indicates the orientation of the Z axis of the detector from South or North to East. Gas flow rate is the rate of the gas circulation.

| Run number  | Date                  | Live time [days] | Detector orientation | Gas circulation rate [mL/min] |
|-------------|-----------------------|------------------|----------------------|------------------------------|
| Run14-1     | 2013/7/17 to 2013/9/16| 17.10            | S60E                 | 500                          |
| Run14-2     | 2013/10/17 to 2013/11/14| 14.52          | S60E                 | 500                          |
| Run14-3     | 2014/01/29 to 2014/3/12| 25.34            | S60E                 | 500                          |
| Run16-1     | 2016/1/14 to 2016/3/10| 42.28            | S60E                 | 1000                         |
| Run16-2     | 2016/3/25 to 2016/6/28| 69.94            | S60E                 | 1000                         |
| Run17-1     | 2016/6/28 to 2016/8/24| 26.16            | S60E                 | 500                          |
| Run18-2     | 2016/9/1 to 2016/10/19| 41.43            | N76E                 | 700                          |
| Run18-3     | 2016/10/20 to 2017/1/19| 66.86          | N76E                 | 700                          |
| Run18-4     | 2017/1/26 to 2017/4/21| 49.51            | N76E                 | 700                          |
| Run18-5     | 2017/4/27 to 2017/8/8 | 81.71            | N76E                 | 700                          |
| Total       | 2013/7/17 to 2017/8/8 | 434.85           |                      |                              |

Initial results from Run14-1 and Run14-2 data with a live time of 31.62 days were previously reported [6]. Since then, additional data corresponding to 403.23 live-days have been accumulated. The total exposure was about 14 times of that of the initial results. The Z axis of the detector was aligned to S30E for the first half and to S76E for the second half to minimize the potential systematic uncertainties. The gas circulation rate was changed a few times as listed in the table aiming to check the effect on the gas gain stability and radon background. No significant effect due to either factor was observed. The data accumulated in Runs 15 and 18-1 were not used for the analysis because the system suffered from electronic noise and the DAQ system was out of condition in the corresponding runs, respectively.
3.2. Detector stability and data correction

The detector gas was filled at the beginning of each sub-run and then circulated without any change during the sub-run. Because the detector performance changes mainly due to the deterioration of the chamber gas, it was monitored for the data correction. This study was new for this work since a typical data-taking period without gas change was longer than those in the previous runs.

3.2.1. Gas gain correction. The gas gain was monitored throughout the measurement by the energy spectrum of $\alpha$ particles from the radon progeny which have a peak at around 6 MeV. Observed gas gains as a function of the elapsed time are shown in Fig. 7 with blue points. It was seen that the gas gain decreased due to the out-gas and the leaks of the chamber. The gains were fitted with a linear function and the conversion factors were corrected so that the obtained line became constant. The corrected gas gains are also shown in Fig. 7 with red points. The event energy was corrected before the event selection.

![Fig. 7: Time dependence of gas gains before (blue) and after (red) correction.](image)
3.2.2. **TS correction.** TSs were also observed to decrease as a function of time, mainly due to the gain decrease. This is an independent observable from the energy information, which was corrected by the gain correction, and the TSs needed to be corrected independently. As described in Section 2.3, TSs were important cut parameters. Time dependence of the TS was studied and used for the correction to recover the inefficiency due to the decrease of the TS. The time dependence of the mean values of $TS_X$ and $TS_Y$ for the 50-60 keV energy-bin are shown in Fig. 8 with blue points. The TSs were corrected in the same manner as for the gain correction and the corrected ones are shown with red points. The correction functions were prepared for each 10 keV energy bin and the TSs were corrected before the TS cuts.

![Graph showing time transition of TSs](image.png)

**Fig. 8:** The time transition of the TSs. The TS of $X$ and $Y$ are shown in the left and right panels, respectively. The blue and red marks indicate the TS before and after corrections, respectively.
3.3. Results

The data went through the selection described in Section 2.3. Energy spectra at each selection step are shown in Fig. 9. The lower energy bound was set to 50 keV, below which no direction sensitivity was measured. The upper energy bound was set to 400 keV with consideration of the recoil energy spectrum by WIMPs. It can be seen that the L cut rejected $\gamma$-rays below 200 keV. The TS, R, and $\theta$ cuts were effective throughout the energy range of interest. A sin$\theta$ distribution before the $\theta$ cut is shown in Fig. 10 (corresponding to the green spectrum in Fig. 9) to demonstrate the effect of the newly introduced $\theta$ cut. Our previous study indicated that the $\mu$-PIC was contaminated with radioactive isotopes such as $^{238}$U and $^{232}$Th. Alpha-rays were emitted from these radioactive isotopes, causing background events. These up-going background events were found at a peak around one in the sin$\theta$ distribution. They were effectively rejected by the $\theta$ cut. A total reduction of four orders of magnitude was realized at 50 keV, whereas the detection efficiency of the nuclear recoil was retained at $\sim 10\%$ as discussed in Section 2.3.

![Energy spectra](image)

Fig. 9: Obtained energy spectra in this work at each cut-step. The unit of the vertical axis is counts/10 keV.

The "effective" energy spectra of this work and our previous work are shown in Fig. 11. The "raw" energy spectra after all cuts were unfolded with the nuclear detection efficiencies so that the effective energy spectra could be compared to one another. It is seen that the effective count rate was reduced by a factor of 4 from the previous run at 50 keV. This is due to the newly introduced $\theta$ cut. The sky-map after all cuts is shown in Fig. 12. The direction of each event is plotted with a blue point with the corresponding direction of the constellation Cygnus. Two trajectory loops for the Cygnus direction are seen indicating the orientation change of the detector between Runs 17 and Runs 18. The gray hatched areas are the cut area and some Cygnus directions corresponding to the events in the selected area are shown there.
Fig. 10: Measured $\sin \theta$ distribution of the nuclear tracks in the energy range of 50 - 400 keV after the R cut.

Fig. 11: Measured "effective" energy spectrum (red histogram). The result of the previous work described in Ref. [6] is shown with blue histogram. Both spectra were unfolded with the detection efficiency of nuclear tracks for comparison.

3.4. Systematic Errors
The systematic errors relevant to the directional analysis are summarized in Table 3. Because the directional analysis was performed by comparing distributions of the angle between the recoil direction and direction of the WIMP-wind, or the $\cos \theta_{\text{Cyg}}$ spectrum, the systematic errors in the expected rate of this spectrum were studied. The error ratio is the ratio of 1 $\sigma$
error to the mean value for each parameter. The effects to these parameters on the $\cos \theta_{Cyg}$ spectrum were estimated by taking the ratio of the entries of $\pm 1 \sigma$ spectrum to that of mean spectrum at the maximum bin of $\cos \theta_{Cyg}$ spectrum (e.g. 0.5~1.0 bin in Fig.14). The largest contribution was found to be the angular resolution, which would change the shape of the spectrum. The head-tail determination also affects the shape, whereas its effect was found to be small compared with the angular resolution. The energy resolution would change the total rate of the $\cos \theta_{Cyg}$ spectrum. These errors will be used in the following section for the directional analysis.

Table 3: Systematic errors. The ratio is the error ratio and the effects on the shape of $\cos \theta_{Cyg}$ spectrum to the corresponding parameters.

| Systematic error          | mean | error (1 $\sigma$) | error ratio | effect on shape of $\cos \theta_{Cyg}$ spectrum |
|---------------------------|------|--------------------|-------------|-----------------------------------------------|
| Angular resolution        | 36°  | 4°                 | 11%         | 7.4%                                          |
| Energy resolution         | 13%  | 1%                 | 8%          | 1.5%                                          |
| Head-tail determination   | 53.4%| 0.5%               | 1%          | 1.4%                                          |
3.5. Dark matter limits

WIMP-nucleon cross section limits were obtained by a 3d-vector directional analysis. Astrophysical parameters, nuclear parameters, and detector responses are listed in Table 4. The main scheme of this method serves to compare the measured and expected $\cos \theta_{\text{Cyg}}$ spectrum. The measured $\cos \theta_{\text{Cyg}}$ with raw number of events are compared with the expected $\cos \theta_{\text{Cyg}}$ spectrum considering the detector response.

Most of the methods were unchanged from our previous work [6]. The main differences are that four bins in $\cos \theta_{\text{Cyg}}$ covering $-1$ to $1$ (previous 2 bins from $0$ to $1$) were used and a binned likelihood-ratio method used in Refs. [13, 14] was adopted.

Table 4: Astrophysical parameters, nuclear parameters, and detector responses

| WIMP velocity distribution | Maxwellian |
|---------------------------|------------|
| Maxwellian velocity dispersion | $v_0 = 220$ km/s |
| Escape velocity | $v_{\text{esc}} = 650$ km/s |
| Local halo density | $\rho_{\text{DM}} = 0.3$ GeV/cm$^3$ |
| Spin factor of $^{19}$F | $\lambda^2 J(J+1) = 0.647$ |
| Energy resolution at 50 keV | $(7.0 \pm 0.5)$ keV |
| Angular resolution at 50 - 100 keV | $(36 \pm 4)$° |
| Head-tail Precision at 50 - 100 keV | $(53.4 \pm 0.5)$% |

A $\chi^2$ value for a given WIMP mass and energy bin was defined as

$$\chi^2(\sigma_{\chi-p}^{\text{SD}}) = 2 \sum_{i=0}^{3} \left[ N_i^{\text{exp}}(\sigma_{\chi-p}^{\text{SD}}) - N_i^{\text{data}} \right] + N_i^{\text{data}} \ln \left( \frac{N_i^{\text{data}}}{N_i^{\text{exp}}(\sigma_{\chi-p}^{\text{SD}})} \right) + \sum_{j=0}^{2} \alpha_j^2$$  \hspace{1cm} (12)

$$\alpha_j = \frac{\xi_j}{\sigma_j}.$$  \hspace{1cm} (13)

Here, the subscript $i$ is the bin number of the $\cos \theta_{\text{Cyg}}$ distribution and the subscript $j$ is the type of the systematic errors ($j = 0, 1$ and 2 correspond to the angular resolution, the energy resolution and the head-tail determination, respectively). $N_i^{\text{exp}}(\sigma_{\chi-p}^{\text{SD}})$ is the expected number of events for the WIMP-proton SD cross section of $\sigma_{\chi-p}^{\text{SD}}$, and $N_i^{\text{data}}$ is the number of observed events. Nuisance parameters $\alpha_j$ were introduced to consider the systematic errors. Here $\xi_j$ and $\sigma_j$ are the shift from the central value and the systematic errors listed in Table 3, respectively. The $\chi^2$ values on a $\alpha_0$-$\sigma_{\chi-p}^{\text{SD}}$, $\alpha_1$-$\sigma_{\chi-p}^{\text{SD}}$ and $\alpha_2$-$\sigma_{\chi-p}^{\text{SD}}$ planes are shown in the left, center and right panels of Fig. 13, respectively. Here the energy bin and the WIMP mass are 60-70 keV and 150 GeV/c$^2$, respectively.

The measured and best-fit (minimum $\chi^2$) $\cos \theta_{\text{Cyg}}$ histograms are shown in Fig. 14. The value of minimum $\chi^2$ over degree of freedom is 9.8/3 at $\alpha_0 = 0.6$, $\alpha_1 = 0$ and $\alpha_2 = -0.1$. Because no significant WIMP excess was found, 90% confidence level (C.L.) upper limits were set on the WIMP-proton cross section. A likelihood ratio $L$ was defined by Eq. (14),

$$L = \exp \left( -\frac{\chi^2(\sigma_{\chi-p}^{\text{SD}}) - \chi^2_{\text{min}}}{2} \right),$$  \hspace{1cm} (14)

where $\chi^2_{\text{min}}$ is the minimum $\chi^2$ value. $L$ values are shown in Fig. 15 as a function of $\sigma_{\chi-p}^{\text{SD}}$. 

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Fig. 13: $\chi^2$ values as function of $\alpha_0$(left), $\alpha_1$(center), $\alpha_2$(right) and $\sigma_{\chi\rightarrow p}^{SD}$. The energy bin and the WIMP mass are 60-70 keV and 150GeV/c$^2$, respectively.

The 90% C.L. upper limit was obtained using the relation defined by Eq.(15).

$$\frac{\int_0^{\sigma_{\chi\rightarrow p}^{SD}\text{limit}} \mathcal{L} d\sigma_{\chi\rightarrow p}^{SD}}{\int_0^{\infty} \mathcal{L} d\sigma_{\chi\rightarrow p}^{SD}} = 0.9,$$

(15)

where $\sigma_{\chi\rightarrow p}^{SD,\text{limit}}$ is the 90% C.L. upper limit of the $\sigma_{\chi\rightarrow p}^{SD}$. $\sigma_{\chi\rightarrow p}^{SD,\text{limit}}$ is indicated with a red line in Fig. 15. An upper limit of 421 pb was obtained in this case.

Fig. 14: Measured (black) and calculated $\cos \theta_{\text{Cyg}}$ distributions. The blue and red histograms are the best-fit and the 90% C.L. ones, respectively. The energy bin and the WIMP mass are 60-70 keV and 150GeV/c$^2$, respectively.
Fig. 15: $\chi^2$ distribution at minimum $\alpha$ in the energy range of 60-70 keV for 150 GeV/$c^2$ WIMP. The 90% C.L. upper limit of the $\sigma^\text{SD}_{\chi-p}$ is indicated by a red line.

Fig. 16: Limits of SD WIMP-proton cross section as a function of WIMP mass. The red thick solid line is the result of this work (3d-vector directional method). The blue thin line labeled “NEWAGE2015” is our previous result. One of the interpretation of the DAMA’s results shown in Ref. [15] is shown as ”DAMA allowed (NaI)”. Blue and black solid-lines show the limits set by gas detectors with directional and conventional analysis, respectively.
The SD WIMP-proton cross section limits obtained by scanning the WIMP mass and energy bin are shown with a red line in Fig. 16. Limits with a 3d-vector tracking method was obtained for the first time by this work. The 90 % SD WIMP-nucleon cross-section upper limit of 421 pb for a 150 GeV/c^2 WIMP was obtained. The directional limits below 150 GeV/c^2 WIMP mass were improved by this work owing to the newly-introduced \( \theta \)-cut. Limits above 150 GeV/c^2 were not similar to our previous limits due to the statistical fluctuation.

4. Discussion
Three-dimensional tracking with head-tail sensitivity (3d-vector tracking method) has been discussed as an "ideal case" for the directional dark matter search because it requires the smallest number of events to discover standard halo WIMPs together with its possibility for unexpected discoveries\[4, 16–18\]. This work demonstrated the first dark matter search with a 3d-vector tracking method. In this study we used the skewnesses of the TOT distributions of \( X \) and \( Y \) for the head-tail determination. There is another axis, \( Z \), or the FADC waveform, which can also be used to determine the head-tails. The waveforms can be analyzed with \( X \) and \( Y \) parameters and this redundancy can be used to improve the head-tail determination power in the future analysis. In the other hand as is seen in Fig. 9, background events limited the sensitivities of the 3d-vector directional dark matter search. Therefore, it is necessary to reduce the background in addition to develop large-sized detectors. The main background was found to be the \( \alpha \)-rays from the \( \mu \)-PIC \[6\]. Although the newly-introduced sin\( \theta \) cut worked well, it is necessary to reduce the background itself at a hardware level. A \( \mu \)-PIC with a low rate of \( \alpha \)-ray emission was developed and installed in NEWAGE-0.3b’\[19\]. Another interesting R&D item which would accelerate the sensitivity improvement of the directional dark matter searches would be the use of the negative-ion gas. This type of gas, in which negative ions are drifted instead of electrons, first drew attention because of the small diffusion\[20\]. Then it was demonstrated that some variations of this type of gases make the fiducialization in the Z-direction (drift-direction) possible. This breakthrough was demonstrated first with CS\(_2\)-based gas mixture and then pure SF\(_6\)\[21, 22\]. Large-volume negative-ion TPCs with low-background materials would make the dark matter search possible even beyond the neutrino floor where large-mass detectors without direction-sensitivity would rapidly lose their searching powers\[4\].

5. Conclusions
The first 3d-vector directional dark matter search using the NEWAGE-0.3b’ detector was performed. The search was carried out from July 2013 to August 2017 (Runs14 to Runs18). The total live time was 434.85 days corresponding to an exposure of 4.51 kg-days which is about 14 times larger than that of our previous measurement (NEWAGE 2015). The 90 % C. L. SD WIMP-proton cross section limit of 421 pb for a 150 GeV/c^2 WIMP was obtained. This is the first experimental dark matter limit obtained with a 3d-vector tracking method.

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