Direction-sensitive dark matter search with a three-dimensional gaseous tracking detector

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Abstract. NEWAGE is a direction-sensitive direct dark matter search experiment with a three-dimensional gaseous tracking detector (μ-TPC). Our goals are detection of the dark matter - nucleus scattering signal and the investigation of kinematics of the dark matter in the Galaxy. A dark matter search experiment with the NEWAGE-0.31 detector was performed from Jul. 2013 to Aug. 2016 (RUN14 to Run17). The total live time is 230.16 days which is about 8 times larger than that of our previous measurement. In the analysis, the event selection was improved and the background was reduced to about 1/3 at 50 keV. This work is important to investigate the properties of the dark matter in the Galaxy in the future dark matter research.

1. Introduction

Dark matter is one of the most important mysteries in particle physics and astrophysics. Cosmological observations show strong evidences that the dark matter constitutes about 27% of the universe [2]. Although many experiments (direct, indirect and collider experiments) have been performed in search for the dark matter, the nature of the dark matter is still unknown[3]. Weakly Interacting Massive Particles (WIMPs) are considered as one of the candidates of the dark matter and the direct detection experiments pursue for the elastic scattering of the WIMP and nucleus. With a natural assumption that the dark matter is trapped gravitationally in the Galaxy, the solar system will receive the dark matter “wind” because of the rotation around the center of the Galaxy. Measurement of the direction of nuclear recoil is thought of as a reliable detection method of the positive signature of the dark matter[4, 5]. Dark matter search experiments using gaseous detectors can measure not only the energy spectrum but also the directions of the nuclear recoil tracks. NEWAGE is a direction-sensitive direct dark matter search experiment using a micro time-projection-chamber, or a μ-TPC. In this study, we discuss the recent results of the NEWAGE experiment. In section 2, we describe the detector system for this work. In section 3, the latest results are shown and the conclusions are presented in section 4.
2. NEWAGE

2.1. Detector

The NEWAGE-0.3b' detector is set in an underground laboratory at Kamioka Observatory (Figure 1), Gihu, Japan[1]. The -TPC consists of a two-dimensional imaging device “micro pixel-chamber(µ-PIC)”, a gas electron multiplier (GEM), and a detection volume \((30 \times 30 \times 41 \text{ cm}^3)\) filled with CF\(_4\) gas at 0.1 atm(Figure 2). Because the diffusion of a drifting electron is small in CF\(_4\) gas and fluorine has a large spin-dependent (SD) WIMP-proton cross-section, CF\(_4\) is chosen for this experiment. The µ-PIC is a variation of the micro-patterned gaseous detectors (MPGDs). The effective area of the µ-PIC for the NEWAGE-0.3b’ is \(30.72 \times 30.72 \text{ cm}^2\), and it has 768 + 768 orthogonally-formed strips with a pitch of 400 µm. Anode electrodes with a diameter of 50 µm are formed on the strips in a circular ring cathode electrodes of 240 µm in diameter. Gas amplification occurs around the anode electrodes and the same amount of negative and positive charge is read from the anode and cathode electrodes, respectively. The Charge from the anode and cathode electrodes are read through the strips. The GEM is placed 4 mm above the µ-PIC as a sub-amplifier to ensure the gas gain. The effective area of the GEM \((31 \times 32 \text{ cm}^2)\) covers the entire surface of the µ-PIC. The GEM is made of a 100 µm thick liquid crystal polymer, the hole size and pitch are 70 µm and 140 µm, respectively. The combined gas gain of µ-PIC×GEM is about 2500. Electric field is formed by a drift plane and 1 cm-spaced wires on the side walls of the detection volume region. Polyetheretherketone was used as the material for the side walls in the NEWAGE-0.3b’. The µ-TPC was placed in a 5 mm thick stainless steel vacuum vessel.

2.2. Data acquisition system

A data acquisition (DAQ) system dedicated to the µ-PIC readout is used for the NEWAGE-0.3b’. The system records two types of data : “charge” and “track.” To obtain “charge” data, analog signals from 768 cathodes were amplified an grouped down to four channels. Then, waveforms of the four channels were recorded using a 100-MHz flash analog-to-digital-converter (FADC). The summed waveforms (FADC-sum) were used to calculate the energy deposition of the tracks. The “track” data record addresses and time-over-threshold (TOT) of all strips hit of each event. The TOT is the time between rising and falling edges crossing the threshold, which roughly corresponds to the deposited energy on the individual strips.

Figure 1. Outer view of the NEWAGE-0.3b’ system in Kamioka Underground Laboratory. This system consists of the µ-TPC, the gas GEM. Detection volume of the NEWAGE-0.3b’ circulation system and the electronics(DAQ). Figure 2. Schematic view of the µ-TPC. µ-system in Kamioka Underground Laboratory. TPC consists of a drift cage, a µ-PIC and a gas circulation system and the electronics(DAQ).
3. Dark matter search

3.1. Data set

Dark matter search experiment with the NEWAGE-0.3b' have been performed in Kamioka underground laboratory since Jul. 2013 (Run14-1). The data accumulated during these measurements are listed in Table 3.1. Initial results used the data from Run14-1 and Run14-2 with an exposure of 0.327 kg-days previously [1]. Since then, a total 200 live day’s data were accumulated until Aug. 2016. In this study, a data set with a total live time of 230.16 days corresponding to an exposure of 2.38 kg-days is used. The statistics is about 8 times of the first results.

| Run number   | Measured date          | Live time | Mass   | Exposure   |
|--------------|------------------------|-----------|--------|------------|
| Run14-1      | 2013/7/17 - 2013/9/16  | 17.10 days| 10.36 g| 0.177 kg-days|
| Run14-2      | 2013/10/17 - 2013/11/14| 14.51 days| 10.36 g| 0.150 kg-days|
| Run14-3      | 2014/1/29 - 2014/3/12  | 25.34 days| 10.36 g| 0.263 kg-days|
| Run15-1      | 2015/3/30 - 2015/8/17  | 13.02 days| 10.36 g| 0.135 kg-days|
| Run15-2      | 2015/8/17 - 2015/10/27 | 16.85 days| 10.36 g| 0.175 kg-days|
| Run15-3      | 2015/11/6 - 2016/1/14  | 7.81 days  | 10.36 g| 0.081 kg-days|
| Run16-1      | 2016/1/14 - 2016/3/10  | 42.28 days| 10.36 g| 0.438 kg-days|
| Run16-2      | 2016/3/25 - 2016/6/28  | 66.79 days| 10.36 g| 0.692 kg-days|
| Run17-1      | 2016/6/28 - 2016/8/24  | 26.46 days| 10.36 g| 0.274 kg-days|
| **Total**    | **2013/7/17 - 2016/8/24**| 230.16 days| 10.36 g| 2.385 kg-days|

3.2. Event Selection

The event selection criteria was almost the same as the one used in the previous measurement except one [1]. A fiducial volume of $28 \times 24 \times 41$ cm$^3$ was selected from the detection volume of $30.72 \times 30.72 \times 41$ cm$^3$. This cut mainly rejects protons and electrons from the wall of the detection volume and the 10B plate. The gamma-ray and the alpha-ray background are cut by the following criteria. Because the energy deposition per unit distance of an electron is much smaller than that of a nucleus, tracks of electron events should be long and non-continuous compared to tracks of nuclear events. The track length and the energy deposition are quantified by two parameters: “length” and “TOT-sum”. “length” is calculated as follows. In the x-z and y-z planes, rising points are fitted with straight lines. Here, the rising points have information about the track shape, while the time durations (TOTs) correspond to the energy deposition. Then, the range of rising points along the fitted line is calculated on each plane and the “length” in the 3D space is calculated by quadrature. “TOT-sum,” is the sum of the TOTs of all strips. The TOT of a strip is the length between the blue (rise time) and black (fall time) points along the strip in Figure 3. Thus, the TOT-sum of a single event is the total number of blue, red, and black points, where the red points lie between the start and end points of the event. Besides, because the drift length of the alpha-ray background from radioactive impurities contaminating the $\mu$-PIC is short, gas diffusion is small, and the track shape is close to a straight line. In order to discriminate this alpha-ray background by using track shape, ”roundness” is defined by Eq. (1) as the extent to which the shape of the rise points.

$$\text{roundness}_x = \frac{\sum_{i} N_x (z_{rise} - a_x x - b_x)^2}{N_x}, \quad \text{roundness}_y = \frac{\sum_{j} N_y (z_{rise} - a_y y - b_y)^2}{N_y}$$

$$\text{roundness} = \min(\text{roundness}_x, \text{roundness}_y)$$ (1)
where $N_x$ and $N_y$ are the number of hits on the x and y strips, respectively. $z_{\text{rise}x}$ and $z_{\text{rise}y}$ are the minimum z values, and $(a_x, b_x)$ and $(a_y, b_y)$ are the best-fit straight lines obtained by fitting $(x, z_{\text{rise}x})$ and $(y, z_{\text{rise}y})$, respectively.

In this work, a energy-dependence was added to the TOT-sum cut in order to improve the rejection of the gamma-ray background. The cut criteria are listed below and Figure 4 shows Length-cut, TOT-sum cut and Roundness cut respectively.

- **Fiducial cut**: $-14 \, [\text{cm}] \leq X \, [\text{cm}] \leq +14 \, [\text{cm}], -10 \, [\text{cm}] \leq Y \, [\text{cm}] \leq +14 \, [\text{cm}]

- **Energy cut**: $50 \, [\text{keV}] \leq E \, [\text{keV}] \leq 400 \, [\text{keV}]

- **Length cut**: Length $[\text{cm}] > 0.6 + 0.004 \times E \, [\text{keV}]

- **TOT-sum cut**: 
  
  $\Rightarrow$ TOT-sum $\leq 50$ (NEWAGE2015) 
  
  TOT-sum $\leq 50 + 0.5 \times E \, [\text{keV}]$ (This work)

- **Roundness cut**: roundness $< 0.05$

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**Figure 3.** Track sample measured with a 252Cf run. Left and right panel show the x-z and y-z plane of the track, respectively. Blue and black points show the rise time points and fall time points, respectively.

**Figure 4.** Energy dependence of the track length(Left), TOT-sum after the length cut(Center) and roundness after the length cut and TOT-sum cut(Right). Red and blue points are measured with 252Cf and 137Cs, respectively.
3.3. Results

Figure 5 shows the measured energy spectrum after all cuts applied obtained in this measurement. The blue and red histograms correspond to NEWAGE2015 and this work respectively. The background was reduced to about 1/3 at 50 keV. Direction-sensitive analysis of the limits for WIMP-nucleus SD cross section is ongoing. With an background reduction and statistical improvement, factor three improvement is expected in the sensitivity.

![Figure 5](image)

Figure 5. measured energy spectrum. the red histogram is Run14 - Run17. the blue one is the previous work (NEWAGE2015, Run14-1 and Run14-2 only)

4. Conclusions

A direction-sensitive dark matter search with the NEWAGE-0.3b’ three-dimensional gaseous tracking detector was performed from Jul. 17, 2013 to Aug. 24, 2016. The total live time obtained by this measurement is 230.16 days corresponding to an exposure of 2.38 kg-days, which is about 8 times larger than that of the previous work. With an improvement of the TOT-sum cut the background was reduced about to 1/3 at 50 keV. The direction-sensitive analysis of the limit for WIMP-nucleus SD cross section is ongoing.

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