Application of Micro-TPC to Dark Matter Search

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Abstract

Detection of a WIMP-wind caused by the motion of the solar system around the galactic center might be one of the most reliable methods to identify a positive signature of weakly interacting massive particles (WIMPs). We evaluated the detection feasibility with carbon tetrafluoride (CF_4) gas for spin-dependent (SD) interaction and Xe gas for spin-independent (SI) interaction taking into account the performance of the micro-TPC which is an existing three-dimensional tracking detector. We consequently found that the micro-TPC filled with CF_4 gas can reach the best sensitivity of the current experiments for SD interactions with even a $0.3\,\mathrm{m}^3 \cdot$ year of exposure at Kamioka Observatory. We also found that it is possible to explore the MSSM prediction region via SI and SD interactions with a sufficient exposure ($\sim 300\,\mathrm{m}^3 \cdot$ year).

1 Introduction

In the currently going measurement, an annual modulation is the only feasible method to identify a positive sign of weakly interacting massive particles (WIMPs) which are one of the best candidates for the cold dark matter. The DAMA experiment has reported an annual modulation signal with nine 10 kg NaI(Tl) detectors [1]. However, this method is rather difficult because the modulation amplitude is only a few %, and the background events themselves are likely to have an annual variation. An alternative and more reliable method is detecting the direction-distribution of the WIMP velocity. The distribution is expected to show an asymmetry like a wind of WIMPs at the earth due to the motion of the solar system around the galactic center [2]. This directional asymmetry is very large, and unlikely to be mimicked by any background events. Many attempts to detect this WIMP-wind by measuring the recoil angles have been performed [3, 4, 5, 6]. Among them, gaseous detectors are one of the most appropriate devices for detecting this WIMP-wind because of their fine spatial resolution. We, therefore, studied the detection feasibility of the WIMP-wind taking into account the performance of an existing three-dimensional tracking detector (micro-TPC) whose tracking capability with a fine spatial resolution has been confirmed. In the previous works, gas properties have been studied to detect the WIMP-wind mainly via spin-independent (SI) interactions [4, 5]. We, on the other hand, did not study the detection feasibility of WIMPs via only SI interactions using Xe gas but also spin-dependent (SD) interactions using carbon tetrafluoride (CF_4) gas because WIMP search experiments should be performed both via SI and SD interactions. In particular, since fluorine was found to be one of the best nuclei for the detection of the SD coupled WIMPs [7, 8], we are focusing on the detection of WIMPs with CF_4 gas used as standard gases for time projection chambers (TPC).

In this paper, the calculated detection possibility of the positive WIMP signature using the micro-TPC is described [9].

2 Performance of Micro-TPC

The Micro-TPC which is a gas TPC with a micro pixel chamber (μ-PIC) read out has been developed for measuring three-dimensional tracks of charged particles with fine spatial resolutions [10, 11, 12, 13].

A μ-PIC is a gaseous two-dimensional imaging detector manufactured using printed circuit board (PCB) technology. With PCB technology, large area detectors can potentially be massproduced, which is an inevitable feature for a WIMP search detector. We developed a prototype of the μ-PIC with $10 \times 10\,\mathrm{cm}^2$ detection area. The schematic structure of the μ-PIC is shown in Fig. 1.

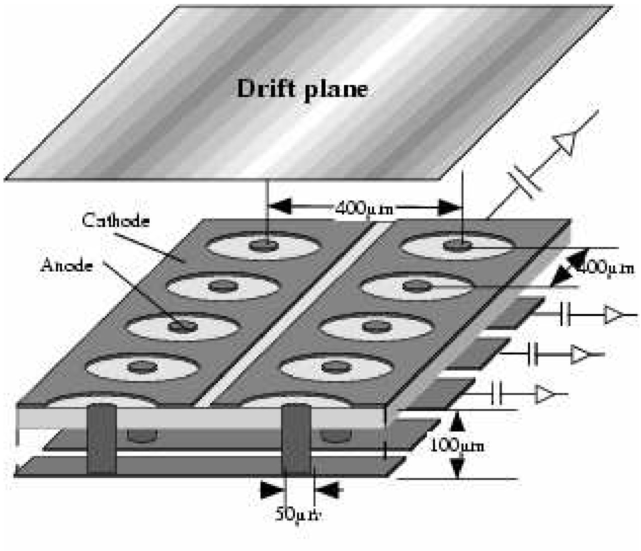

Figure 1: Schematic structure of the μ-PIC.

The μ-PIC is a double-sided PCB with a 100 μm-thick polyimide substrate. 256 anode strips are formed with $400\,\mu$m pitch on one side of the μ-PIC while 256 cathode strips are orthogonally placed on the other side. A gas avalanche occurs around the anode electrodes due to the strong electric field similar to a wire chamber while the electric field is weaker at the cathode edge. As a consequence of the geometrical properties, discharge probability are less and the higher gas gain should be obtained than that of a MicroStrip Gas Chamber (MSGC [14, 15]). Stable operations at high gas gain, therefore, can be realized. The signals from anode strips and cathode strips are amplified and discriminated into LVDS-level signals. Discriminated digital signals are in turn read by a FPGA-based position encoding module (PEM) and synchronized with an internal clock of 20 MHz so that two-dimensional hit positions are calculated by the anode-cathode coincidence within one clock. Together with the timing information from the TPC, three-dimensional tracks are detected as successive points.

In order to study the three-dimensional tracking performance, we measured the tracks of the recoil protons (500 keV–1 MeV) with a radioactive source of ^{252}Cf [16]. In Fig. 2, obtained tracks of the recoil protons are shown by closed circles, and a typical electron track of about 100 keV is also shown by open circles. The distance between track points shown in Fig. 2 was restricted by the clock of the electronics (20 MHz), which we will soon increase to more than 50 MHz.

Fig. 2 also shows flash ADC waveforms of the proton tracks in the plane whose cathode value equals 0, regarded as the Bragg curves. The direction of the tracks are obviously known from the shape of these Bragg curves. From this measurement, the micro-TPC was found to possess sufficient performance to detect the tracks and directions of the charged particles with track length of down to 3 mm. Since the electron tracks are much more winding and have a smaller energy deposition (dE/dx) than those of protons as clearly shown in Fig. 2, the electron tracks are known to be discriminated with high efficiency [16]. According to the geometrical study of the electrodes using three-dimensional simulators [17], we expect that the gas gain increase by a factor of three. The dE/dx threshold will

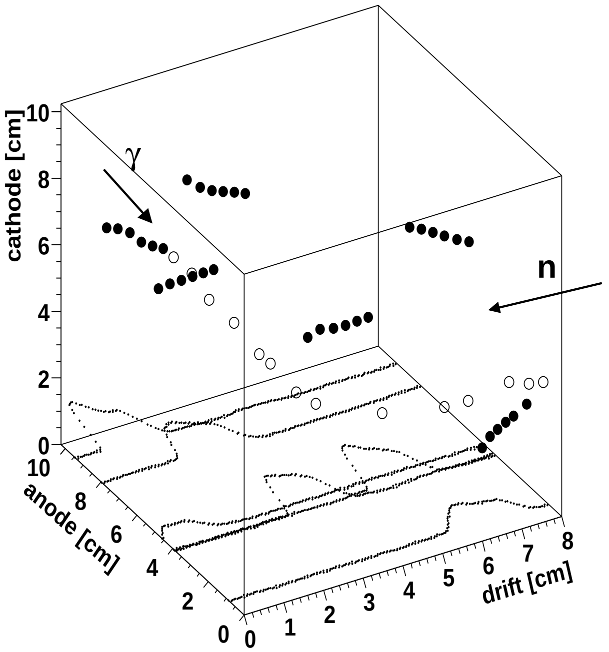

Figure 2: Several three-dimensional proton tracks shown by closed circles and their Bragg curves shown in the plane whose cathode value equals 0. A typical electron track is also shown by open circles.

be then better than 10 keV/cm even with CF_4 gas whose larger W value of 54 eV [18], which is the average energy to produce one electron-ion pair, than argon's W value of 26 eV. We started the study of the properties of CF_4 gas, and found that micro-TPC shows the sufficient high gas gain, ~ 10000. Precise studies on the gas properties will be reported in another paper.

3 WIMP-wind detection possibility

Taking into account the detector performance described in the previous section, we assume that the track length and dE/dx threshold of a micro-TPC as a WIMP-wind detector are 3 mm and 10 keV/cm, respectively. From the calculated energy deposition of the F ion by using SRIM2003 [19] and the scaled track length of the measured value [20], we consequently knew that 25 keV F ion has a range of roughly 3 mm in 20 Torr of CF_4 and the electron diffusion should be suppressed to lower than $\sigma < 1$ mm in order to obtain the track direction [9]. Since the electron diffusion was found to be less than 1 mm by limiting the drift length to 50 cm in 20 Torr of CF_4 gas [9], we assume the full information on recoil tracks including their direction which is called "full-tracking (FT)" in Ref. [9] can be obtained. We also knew that 25 keV Xe ion has a range of roughly 3 mm in 5 Torr of Xe by using SRIM2003 [19].

We calculated the energy spectrum of the recoil nucleus by following Ref. [21] and the direction distribution by following below expression [3, 7],

$$\frac{dR}{dE\,d\cos\gamma} \propto \exp\left[\frac{(v_{\rm s}\cos\gamma - v_{\rm min})^2}{v_0^2}\right] \tag{1}$$

where R is the count rate, E is the recoil energy, γ is the recoil angle, $v_{\rm s}$ is the solar velocity with respect to the galaxy, $v_{\rm min}$ is the minimum velocity of WIMPs that can give a recoil energy of E, and v_0 is the Maxwellian WIMP velocity dispersion. We used the astrophysical and nuclear parameters given in Table 1. We assumed that the γ-rays, β-rays, and α-rays are discriminated by 100% efficiency, and that fast neutrons dominate the background. The neutron background in 50 cm water shield was estimated by using the measured fast neutron flux at Kamioka Observatory [22] and the G4HPmodel+ENDF/B-VI extension to the Geant4 simulation package [23].

Dark matter density	$0.3\,{\rm GeVc^{-2}/cm^3}$
Velocity distribution	Maxwellian
Velocity dispersion	$v_0 = 220\ {\rm kms^{-1}}$
Escape velocity	$v_{\rm esc} = 650\ {\rm kms^{-1}}$
Solar velocity	$v_{\rm s} = 244\ {\rm kms^{-1}}$
Spin factor of ^{19}F (100 %)	$\lambda^2 J(J+1) = 0.647$

Table 1: Astrophysical and nuclear parameters used for the calculation.

Simulated $\cos\gamma$ distribution for 20 Torr CF_4 gas are shown in Fig. 3. The WIMP signals, neutron background, and the total observable events are shown in the hatched histograms, filled ones, and the ones with errorbars, respectively. The asymmetry-detection confidence level (ADCL) was defined as,

$$ADCL = \frac{N_{\rm L} - N_{\rm S}}{\sqrt{N_{\rm L} + N_{\rm S}}}, \tag{2}$$

where $N_{\rm L}$ and $N_{\rm S}$ are the number of events with $\cos\gamma > 0$ and that with $\cos\gamma < 0$, respectively.

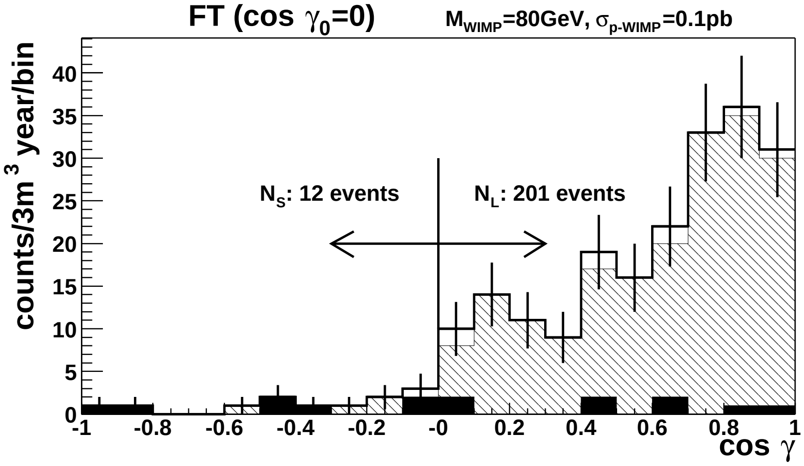

Figure 3: Simulated recoil angle distributions for the 20 Torr of CF_4 gas [9]. WIMP signals, neutron background, and the total observable events are shown in the hatched histograms, filled ones, and the ones with errorbars, respectively.

We then calculated the SI and SD $3\,\sigma$ detection sensitivities to the limits on WIMP-nucleon and WIMP-proton cross section as a function of the WIMP mass, respectively. Here $3\,\sigma$ detection sensitivities were defined as the smallest cross section for which we observe $ADCL = 3\,\sigma$. Obtained SI sensitivities for Xe gas and SD ones for CF_4 gas are shown in Fig. 4 and Fig. 5, respectively. In particular, even a $0.3\,{\rm m}^3 \cdot$ year of exposure at Kamioka Observatory can reach the best sensitivity

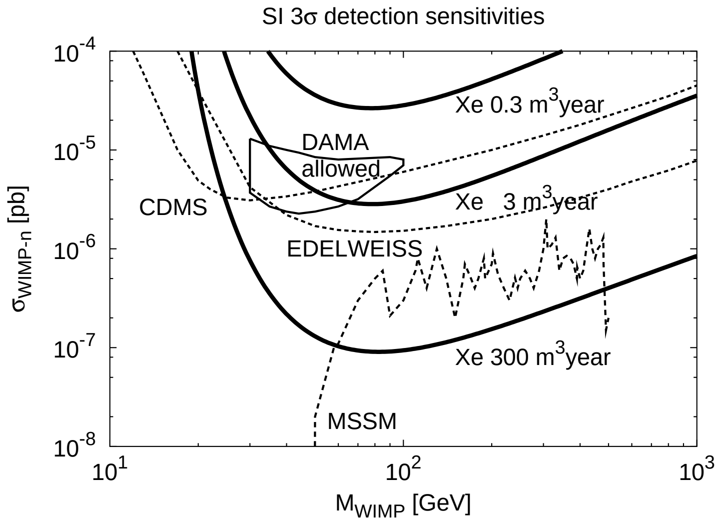

Figure 4: Estimated SI $3\,\sigma$ detection sensitivities at Kamioka Observatory for three exposure shown by thick solid lines. Limits from other experiments [24, 25] are shown by thin dotted lines. DAMA's allowed region [1] is shown by a closed contour. MSSM predictions [27] are also shown by a thin dotted line.

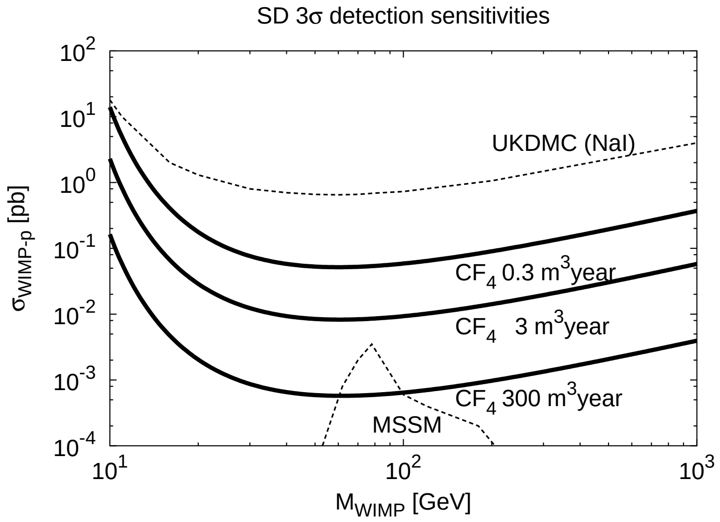

Figure 5: Estimated SD $3\,\sigma$ detection sensitivities at Kamioka Observatory for three exposure shown by thick solid lines. Limits from the UKDMC experiment [26] are shown by a thin dotted line. MSSM predictions [27] are also shown by a thin dotted line.

of the current experiments for SD interactions. Furthermore, it is possible to explore the MSSM prediction region via SI and SD interactions with a sufficient exposure ($\sim 300\,\mathrm{m}^3 \cdot \mathrm{year}$).

A prototype micro-TPC as a WIMP detector with a detection volume of $30 \times 30 \times 30\,\mathrm{cm}^3$ is now being manufactured. Since the fundamental manufacturing technology is already established, a large volume detector ($\sim 1\,\mathrm{m}^3$) for the underground measurement will soon be available.

4 Conclusion

In conclusion, we found that micro-TPC filled with CF_4 gas is a promising device for the WIMP-wind detection via SD interactions. Even a $0.3\,\mathrm{m}^3 \cdot \mathrm{year}$ of exposure at Kamioka Observatory can reach the best sensitivity of the current experiments. With a sufficient exposure ($\sim 300\,\mathrm{m}^3 \cdot \mathrm{year}$), it is expected that the sensitivities of micro-TPC as WIMP detector can explore the MSSM region for SI and SD interactions.

Acknowledgements

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