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Detecting the WIMP-wind via spin-dependent interactions

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Abstract

Revealing the nature of dark matter is one of the most interesting tasks in astrophysics. Measuring the distribution of recoil angles is said to be one of the most reliable methods to detect a positive signature of dark matter. We focused on measurements via spin-dependent interactions, and studied the feasibility with carbon tetrafluoride (CF₄) gas, while taking into account the performance of an existing three-dimensional tracking detector. We consequently found that it is highly possible to detect a positive signature of dark matter via spin-dependent interactions.

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1. Introduction

Existence of the dominant cold dark matter (CDM) became much more concrete by the recent results of the WMAP cosmic microwave background (CMB) all-sky observation with other finer scale CMB measurements (ACBAR and CBI), 2dFGRS measurements, and Lyman α forest data [1]. Best fit cosmological parameters, $h = 0.71^{+0.04}_{-0.03}$, $\Omega_b h^2 = 0.0224 \pm 0.0009$, $\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$, and $\Omega_{tot} h^2 = 1.02 \pm 0.02$, show that the CDM consists about 20% of the energy and dominates the mass of the universe.

Weakly interacting massive particles (WIMPs) are one of the best candidates for CDM. In spite of

quite a few WIMP search experiments, there has not yet been any experimental evidence of WIMP detection [2], except for an indication of an annual modulation signal, reported by the DAMA group [3]. Because the amplitude of an annual modulation signal is only a few %, positive signatures of WIMPs are very difficult to detect with conventional methods, which basically measure the recoil spectrum. Owing to the motion of the solar system with respect to the galactic halo, the direction-distribution of the WIMP velocity that we observe at the earth is expected to show an asymmetry, like a wind of WIMPs. Attempts to detect a positive signature of WIMPs by measuring the recoil angles have been carried out [4–9] ever since it was indicated to be an alternative and more reliable method [10]. Gaseous detectors are one of the most appropriate devices for detecting this WIMP-wind

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[11,12]. Properties of the CS_2 gas, which is sensitive to the WIMP-wind mainly via spin-independent (SI) interactions are mainly studied because of its small diffusions [7,8]. We, on the other hand, are focusing on the detection of WIMPs via spin-dependent (SD) interactions, because WIMPs can basically be detected both via SI and SD interactions. Because fluorine was said and also found to be very effective for a WIMP search via SD interactions, as shown in previous works [13–15], we studied the detection feasibility with carbon tetrafluoride (CF_4) gas, which has been studied very well as one of the standard gases for time projection chambers (TPC) [16,17]. While the use of CF_4 has been proposed by others before [18,19], this is the first in-detail feasibility study, taking into account the performance of an existing three-dimensional tracking detector (μ -TPC) and the measured neutron background flux.

2. μ -TPC

A μ -TPC is a time projection chamber with a micro pixel chamber (μ -PIC) readout, being developed for the detection of tracks of charged particles with fine spatial resolutions [20–23]. A μ -PIC is a gaseous two-dimensional position-sensitive detector manufactured using printed circuit board (PCB) technology. With PCB technology, large-area detectors can, in principle, be mass-produced, which is an inevitable feature for a dark matter detector. We developed a prototype μ -TPC with a detection volume of $10 \times 10 \times 8 \text{ cm}^3$, and studied its fundamental properties with a $\text{Ar-C}_2\text{H}_6$ gas mixture of 1 atm. Anode electrodes are formed with a pitch of $400 \mu\text{m}$, and signals from anode strips and cathode strips are amplified and discriminated into LVDS-level signals. Discriminated digital signals are fed to an FPGA-based position encoding module and synchronized with an internal clock of 20 MHz, so that two-dimensional hit positions can be calculated by the anode-cathode coincidence within one clock. Together with the timing information, three-dimensional tracks are thus detected as successive points. Measured two-dimensional (μ -PIC intrinsic) and three-dimensional position resolutions of the μ -TPC are $120 \mu\text{m}$ [24] and $260 \mu\text{m}$ [25], respectively. We irradiated the μ -TPC with fast neutrons from a radioactive source of ^{252}Cf [26], and tracks of the recoil protons (500 keV–

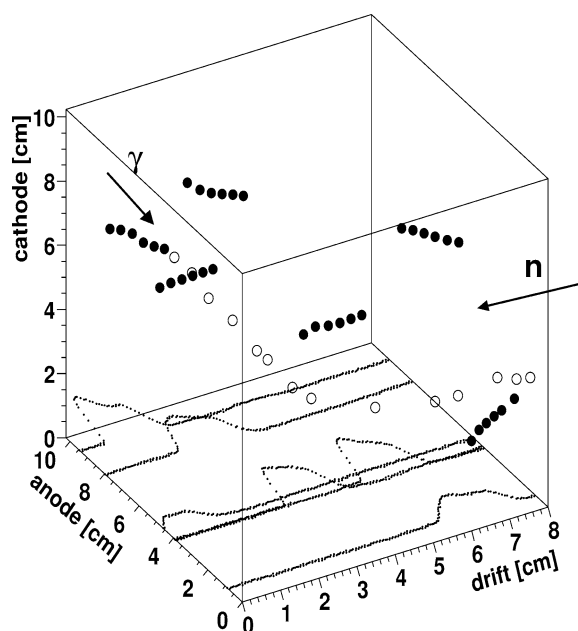


Fig. 1. Several three-dimensional proton tracks and their Bragg curves detected by the μ -TPC filled with a $\text{Ar-C}_2\text{H}_6$ gas mixture. The μ -TPC was irradiated with the fast neutrons and gamma-rays from a radioactive source of ^{252}Cf . Detected tracks of the recoil protons (500 keV–1 MeV) are shown by the filled circles. The FADC data, which can be recognized as the Bragg curves are shown in the cathode = 0 cm plane. A typical track of a Compton-scattered electron is shown by blank circles for reference. The arrows indicate the directions of the incoming primary particles.

1 MeV) were detected, as shown by the filled circles in Fig. 1. The distance between the detected points was restricted by the clock of the electronics (20 MHz), which we will soon increase to more than 50 MHz [25]. This result indicates that a μ -TPC, which can detect tracks of the charged particles down to 3 mm, will be available for the dark matter search experiment. The sums of the all cathode signals recorded by a flash ADC (FADC) are also shown in Fig. 1 in the cathode = 0 plane. We recognized that Bragg curves were well-reproduced by the FADC data, and thus the track directions were obviously known. In Fig. 1, a typical electron track of about 100 keV is also shown by the blank circles. Because the electron tracks are much more winding, and have a smaller energy deposition (dE/dx) than those of protons, gamma-rays are known to be discriminated with high efficiency [26]. Stable operation of the μ -TPC with a dE/dx threshold of 15 keV/cm (gain ~ 5000) for

more than 1000 hours was already realized. We are improving the geometrical structure of the electrodes by using three-dimensional simulators [27], which we expect will increase the gas gain by a factor of three. Then, the dE/dx threshold will be better than 10 keV/cm, even with CF_4 gas, which has a larger W value (average energy to produce one electron–ion pair) than argon ($W_{\text{CF}_4} = 54$ eV, $W_{\text{Ar}} = 26$ eV [28]). We started a study of the detector performance with CF_4 gas, and found that μ -TPC shows a good detector performance (gas gain ~ 10000). Precise studies on the gas properties will be reported in another paper. Based on the detector studies described above, and on-going improvements, we assume that a μ -TPC as a dark matter detector have the properties listed below:

- track length threshold is 3 mm;
- dE/dx threshold is 10 keV/cm;
- gamma-ray discrimination efficiency is close to 100%;
- Bragg curves are detected.

3. WIMP-wind measurement

We studied the feasibility of WIMP-wind detection with CF_4 gas considering the detector characteristics listed above. First, we calculated the energy deposition of a F ion in CF_4 gas. We set the gas pressure at 20 Torr and the recoil energy at 25 keV. Because the binding energy of a C–F in a CF_4 molecule is 4.6 eV, all of the recoil energy is thought to become kinetic energy of the F ion. The energy deposition was calculated by SRIM2003 [29] and the range was scaled by the same manner as discussed in Ref. [7]. The energy deposition was also scaled by the same scaling factor. The range R of the F ion in CF_4 is expressed as a function of the pressure p and the recoil energy E with a good approximation down to $E = 5$ keV in this situation as follows:

$$R = \left(\frac{dE}{dx} \right)_{\text{Ne in Ar}}^{-1} \frac{N_{\text{Ar}}}{N_{\text{CF}_4}} E \frac{760 \text{ Torr}}{p} = k \cdot E p^{-1}, \quad (1)$$

where $(dE/dx)_{\text{Ne in Ar}} \sim 130$ keV/mm [30] is the energy deposition of a Ne ion in Ar gas; $N_{\text{Ar}}/N_{\text{CF}_4}$ is the ratio of the electron density of Ar gas and CF_4 gas. We consequently knew that a 25 keV F ion has a range of roughly 3 mm in 20 Torr CF_4 using $k =$

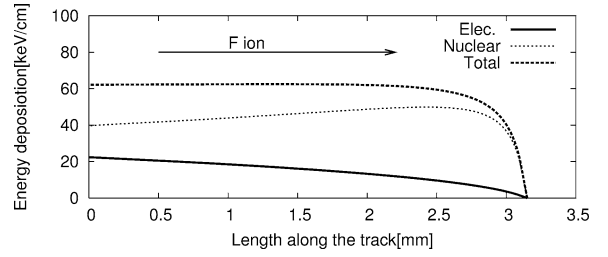


Fig. 2. Calculated energy loss of a F ion of 25 keV in 20 Torr CF_4 gas. The energy loss in the electron field, nuclear field, and the total energy loss are shown by the solid, dotted, and dashed lines, respectively.

2.63 mm Torr/keV. The calculated energy losses of a F ion in CF_4 gas are shown in Fig. 2. The range of an ion is determined by the total (electron + nuclear fields) energy loss, shown in the dashed line. Since the energy loss in the nuclear field has a negligible effect on ionizations, the “visible” energy loss is that in the electron field shown by the solid line. From the calculated energy loss in the electron field, it is seen that the electron diffusion should be suppressed to lower than $\sigma < 1$ mm in order to know the track direction.

In the following discussion, we consider two experimental modes.

- (1) We use the digital hit points for tracking, but do not use the FADC data for determining the track direction. In this case, the recoil angle is known only by the absolute value of its cosine. We hereafter call this semi-tracking, or the “ST” mode.
- (2) We somehow suppress the electron diffusion and use the full information on their tracks, including the direction. We hereafter call this full-tracking, or the “FT” mode.

The FT mode will be realized by limiting the drift length, or by using an electro-negative gas [31]. A magnetic field does not help, however, because the longitudinal electron diffusion cannot be suppressed by the magnetic field. The electron diffusion (σ) along the track path is expressed as $\sigma = \sqrt{2DL/W}$, where D is the diffusion coefficient, L is the drift length, and W is the drift velocity. $D < 1000$ cm²/s [16] and $W > 10$ cm/ μ s are achieved for a reduced electric field of $E/p > 1$ kV/(cm atm), which implies that

Table 1

Astrophysical, nuclear, and experimental parameters used for the calculations. The density of 30 Torr of CF₄ is 155 g/m³

WIMP velocity distribution	Maxwellian
Solar velocity	$v_s = 244$ km/s
Maxwellian velocity dispersion	$v_0 = 220$ km/s
Escape velocity	$v_{\text{esc}} = 650$ km/s
Local halo density	0.3 GeV/cm ³
Spin factor of ¹⁹ F	$\lambda^2 J(J+1) = 0.647$
Target gas	CF ₄
Gas pressure (ST/FT)	30 Torr/20 Torr
Energy threshold (ST/FT)	35 keV/25 keV
Track length threshold	3 mm
Fast neutron flux	$(1.9 \pm 0.21) \times 10^{-6}$ n/(cm ² s)
Neutron shield	50 cm water
M_{WIMP}	80 GeV
$\sigma_{\text{WIMP}-p}^{\text{SD}}$	0.1 pb
Exposure	3 m ³ year

$\sigma < 1$ mm is realized with a drift length of 50 cm in 20 Torr of CF₄ gas. We calculated the recoil angle distributions for the ST and FT modes. We followed Ref. [32] for the energy-spectrum calculation and

$$\frac{dR}{dE d\cos\gamma} \propto \exp\left[\frac{(v_s \cos\gamma - v_{\min})^2}{v_0^2}\right] \quad (2)$$

in Refs. [5,10] for the direction distribution calculation. Here, R is the count rate, E is the recoil energy, γ is the recoil angle, v_s is the solar velocity with respect to the galaxy, v_{\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, nuclear, and experimental parameters given in Table 1. We assumed that the gamma-rays, β -rays, and α -rays are discriminated by 100% efficiency, and that fast neutrons dominate the background. This assumption is reasonable because we can detect three-dimensional tracks with fine samplings in contrast to the two-dimensional tracks discussed in Ref. [7]. The measured fast neutron flux at Kamioka Observatory [33] was used for the calculation. The simulated $\cos\gamma$ distributions for the ST and FT modes are shown in the upper and lower panels of Fig. 3, respectively. The WIMP signals are shown by the hatched histograms, the neutron backgrounds are shown in the filled histograms, and the total observable events are shown in the histograms with error bars. We simply analyzed the asymmetry by comparing the number of events with $\cos\gamma > \cos\gamma_0$ (N_L) and that with $\cos\gamma < \cos\gamma_0$

(N_S), where γ_0 was chosen so that N_L equals N_S for a flat background. The asymmetry-detection confidence level (ADCL) was then defined as

$$\text{ADCL} = \frac{|N_L - N_S|}{\sqrt{N_L + N_S}}. \quad (3)$$

We obtained 5.8σ and 13σ in the ST mode and the FT mode, respectively. Although the ST mode showed a lower confidence level than the FT mode, it was shown that the ST mode is still a very strong method compared to the conventional method to detect the positive signal of WIMPs. Because the direction of the WIMP-wind has a diurnal modulation which goes out of phase with a period of a year, it is unlikely that any background that is isotropically distributed or localized near the detector, would mimic this asymmetry. Even the background that have or could have fixed day/night circadian rhythm does not mimic the WIMP signal because WIMP-wind is expected to be blowing in the same direction during the day now and during the night in six months.

We calculated ADCL values for several parameter sets in order to evaluate its dependence on the experimental parameters. The experimental parameters given in Table 1, except for the gas pressure and the energy threshold are used for the calculation. The result is shown in Fig. 4. It is seen that the ST mode and the FT mode have the largest ADCL values at 30 and 20 Torr, respectively. In Fig. 5, 3σ detection sensitivities to the $\sigma_{\text{WIMP}-p}^{\text{SD}}$ as a function of M_{WIMP} are shown. The parameters given in Table 1, except for M_{WIMP} , $\sigma_{\text{WIMP}-p}^{\text{SD}}$, and the exposure, were used for the calculation. Here, the 3σ detection level was defined as the smallest cross section for which we observe $\text{ADCL} = 3\sigma$. Even the ST method can reach the best sensitivity of the current experiments with a 0.3 m³ year of exposure at Kamioka Observatory. With the FT method, it possible to explore the MSSM prediction region via SD interactions with a sufficient exposure (~ 30 m³ \times 10 years). When we see any implication of the WIMP-wind, a precise study can be performed with the same technology by analyzing the shape of the recoil angle distribution. A prototype WIMP detector with a detection volume of $30 \times 30 \times 30$ cm³ is now being manufactured. Since the fundamental manufacturing technology is already established, a large-volume detector (~ 1 m³) for underground measurements will soon be available.

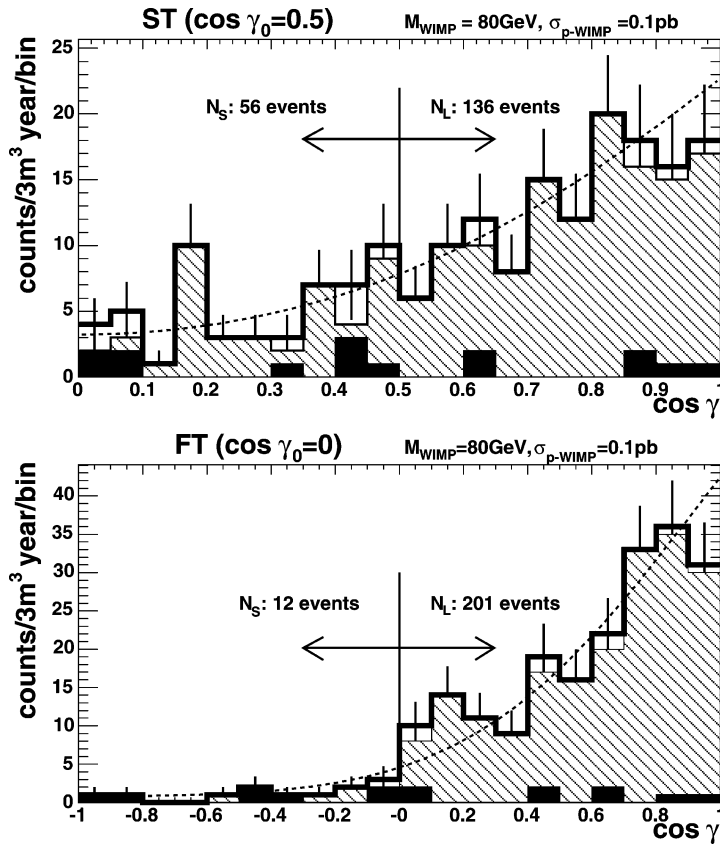


Fig. 3. Simulated recoil angle distributions for the ST (semi-tracking) mode (upper) and the FT (full-tracking) mode (lower). The pressures of the CF₄ gas are 30 and 20 Torr for the ST mode and FT mode, respectively. Neutron background is estimated based on the measured fast neutron flux $(1.9 \pm 0.21) \times 10^{-6}$ n/(cm² s) at Kamioka Observatory and a 50 cm water shield. WIMP signals, neutron background, and the total observable events are shown in the hatched, filled, and solid-line histograms, respectively. Theoretical calculations are also shown by the dashed lines.

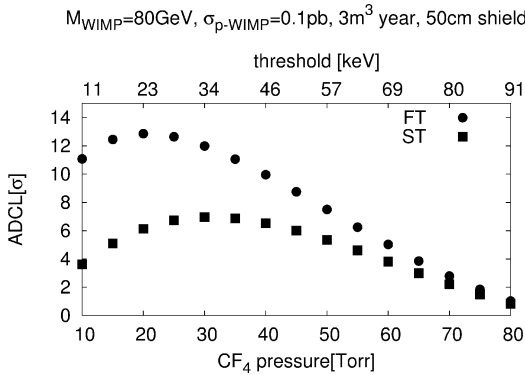


Fig. 4. Asymmetry-detection confidence level (ADCL) [σ] as a function of the gas pressure and the corresponding recoil energy threshold. It is seen that FT (full-tracking) and ST (semi-tracking) modes have different optimum pressures.

4. Conclusions

In this Letter, we have shown that μ -TPC filled with CF₄ gas is a promising device for WIMP-wind detection via SD interactions. By the full-tracking method with sufficient exposure, it is expected that we cannot only detect the WIMP-wind, but can also precisely study the nature of WIMPs.

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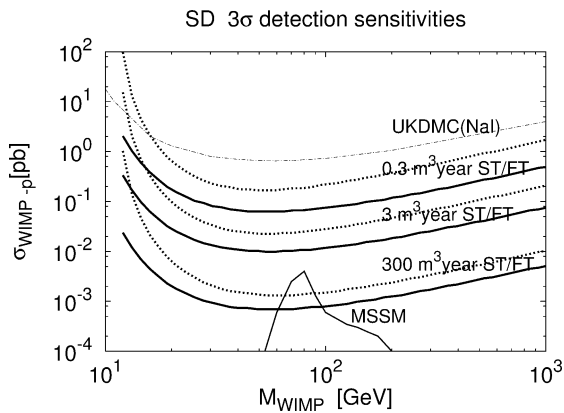


Fig. 5. Simulated 3σ asymmetry detection sensitivities by the measurement at Kamioka Observatory. Sensitivities by the ST (semi-tracking) and FT (full-tracking) modes are shown by the thick dotted and thick solid lines, respectively. Three exposures are considered for each mode. The pressures of the CF_4 gas are 30 and 20 Torr for the ST mode and FT mode, respectively. An experimental result of UKDMC (dashed-dotted) and MSSM predictions (solid) are also shown [34,35].

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