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Development of gaseous tracking devices for the search of WIMPs

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Abstract

The Time Projection Chamber (TPC) has been recognized as a potentially powerful detector for the search of WIMPs by measuring the directions of nuclear recoils, in which the most convincing signature of WIMPs, caused by the Earth's motion around the Galaxy, appears.

We report on the first results of a performance study of the neutron exposure of our prototype micro-TPC with $Ar-C_2H_6$ (90:10) and CF_4 gas at 150 Torr.

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1. Introduction

It is considered by many that the galactic halo is composed of weakly interacting massive particles (WIMPs) as dark matter [1]. These particles could be detected directly by measuring the nuclear recoils produced by their elastic scattering off nuclei in detectors. The most convincing signature of WIMPs appears in the directions of nuclear recoils. It is provided by the Earth's large velocity through the isothermal galactic halo (~230 km/s). Hence, detectors sensitive to the direction of the recoil nucleus would have a great potential to identify WIMPs [2].

Time Projection Chambers (TPCs) with fine spacial resolutions are among such devices, and we are developing a micro TPC, which can detect three-dimensional fine tracks of charged particles [3]. Since the energy deposits of WIMPs to nuclei are only a few tens of keV and the range of nuclei is limited, the micro-TPC should be operated at low pressures.

We also focused on the detection of WIMPs via spin-dependent (SD) interactions and are interested in operating the micro-TPC with CF_4 [4], because ^{19}F has a special sensitivity to SD interactions for its unique spin structure [5].

In the present work, in order to examine the response of the micro-TPC to nuclear recoils at low pressures as a first step, we irradiated a 150 Torr $Ar-C_2H_6$ (90:10 mixture) gas (one of the standard gases for TPCs) and CF_4 with neutrons from ^{252}Cf. The track lengths and deposited energies of Ar, C, and F recoils were investigated.

2. The micro-TPC

The prototype micro-TPC used in this measurements is shown in Fig. 1. The field cage consists of a drift cathode plane and nine 0.2 μm copper wires of 1 cm pitch with connections of 10 MΩ resistor, which forms a uniform electric field in the detection volume of $10 \times 10 \times 10\,cm^3$.

The μ-PIC [6] for 2-dimensional readout is $10 \times 10\,cm^2$ with 256 anode strips and 256 cathode strips each with a 400 μm pitch. We also used a GEM having a 10 cm ×

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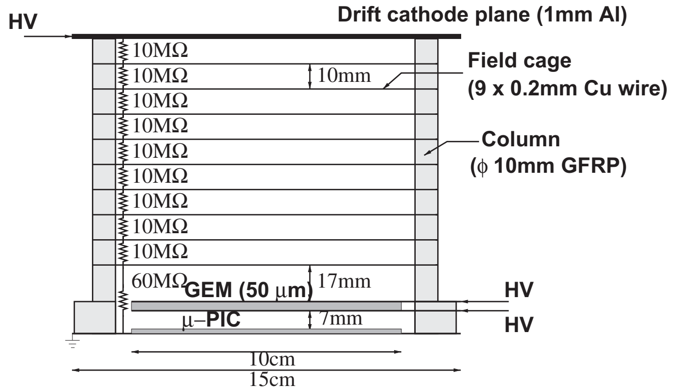

Fig. 1. Schematic diagram of the prototype micro-TPC and the drift-field cage.

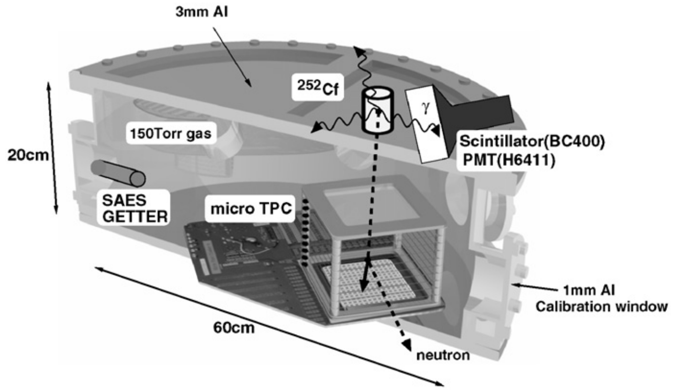

Fig. 2. Setup of this measurement for 150 Torr gas operation.

10 cm^2 sensitive area as a sub-amplification device between the field cage and μ-PIC, as illustrated in Fig. 1, which enables stable operation and avoids discharges with low HV operation of both the μ-PIC and GEM. The details of this GEM are described in Refs. [7,8].

The output charges of 256 + 256 channels are pre-amplified (0.7 V/pC) and shaped (with a gain of 7) and discriminated via ASD chips (4 channels/chip, SONY CXA3653Q) [9]. The pre-amplified signals are summed and digitized by 100 MHz 8 bit flash ADCs in order to determine the deposited energy and the track direction as the waveforms hold the Bragg curve shapes.

The reference threshold voltage (0–100 mV) is commonly supplied to all the ASD chips and all discriminated digital signals are sent to the position encoding module based on FPGAs with an internal clock of 100 MHz, so that the anode and cathode coincident position $=(x,y)$ and the

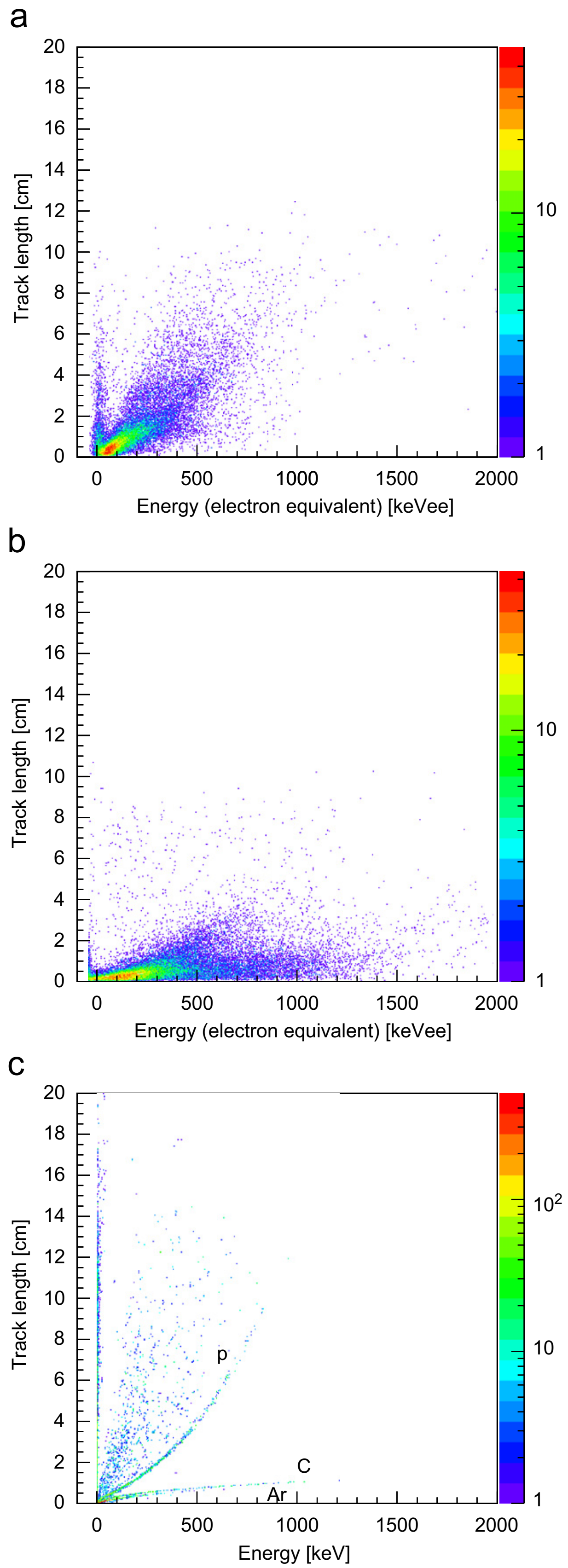

Fig. 3. Track length as a function of deposited energy with 150 Torr Ar−C_2H_6 (90:10): (a) high-gain operation (low dE/dx threshold); (b) low-gain operation (high dE/dx threshold); (c) Geant4 MC simulation without consideration of the diffusion of the drift process, the energy resolution, and the detection threshold. Because the size of the TPC is too small for proton tracks, proton events are scattered in upper regions of the main band.

timing (z) are recorded in the memory module and the tracks of charged particles are reconstructed in software. The tracking performances for electrons, protons, and MIPs are reported elsewhere [3,8].

3. Measurements and results

As illustrated in Fig. 2, the micro-TPC was set in a 6 mm-thick aluminum vessel of 60 cm diameter × 20 cm height. In a typical run, the vessel was evacuated to $\sim 8\times 10^{-3}$ Torr, the SAES GETTER® pump in the vessel was activated, and then the vessel was filled with $Ar{-}C_2H_6$ (90:10) or CF_4 gas to a pressure of 150 Torr and sealed for the duration of the measurement.

For measuring the gas gain and the energy calibration, the gas was irradiated with ^{109}Cd 22 keV and ^{133}Ba 31.0 keV X-rays through a 1 mm thick aluminum window close to the sensitive volume.

We irradiated the micro-TPC with neutrons from a 1 MBq ^{252}Cf source on the top of the vessel. Since one fission decay of ^{252}Cf emits 3.8 neutrons and 9.7 γ-rays on average [10], the γ-rays or neutrons detected by a $10\times 10\times 2\,\mathrm{cm}^3$ plastic scintillator were used as the event trigger.

In the γ/n-triggered events, gamma events would dominate under normal gas gain ($\sim$10 000) operation. Since the $\mathrm{d}E/\mathrm{d}x$ values of the neutron events are much larger than those of gamma events, we operated the μ-PIC and GEM with a rather low gas gain (below 1000) in order to observe the nuclear recoils.

In such different gas gain measurements, we fixed the anode voltage of the μ-PIC and changed the voltage between the GEM electrodes. Below a gas gain of about 2000, our system was not able to measure the ^{109}Cd 22 keV X-ray correctly due to a mismatch of the dynamic range of the ASD chips and the flash ADC; therefore, the deposited energy in low-gain operations was extrapolated from the calibrations with the high gas gain operations.

We evaluated the track length as a function of the measured electron equivalent energy in the following way.

3.1. $Ar{-}C_2H_6$ 150 Torr run

The drift cathode plane was supplied −1 kV, which gave a drift field of 60 V/cm and an electron drift speed of 4.0 cm/μs. The anode voltage of the μ-PIC was fixed at 350 V.

For nuclear recoil measurements, the threshold of the discriminator of the ASD chip was set to 80 mV and the measured track length of events when the GEM voltage was set to 200 V (gas gain of 3000) and 135 V (gas gain of

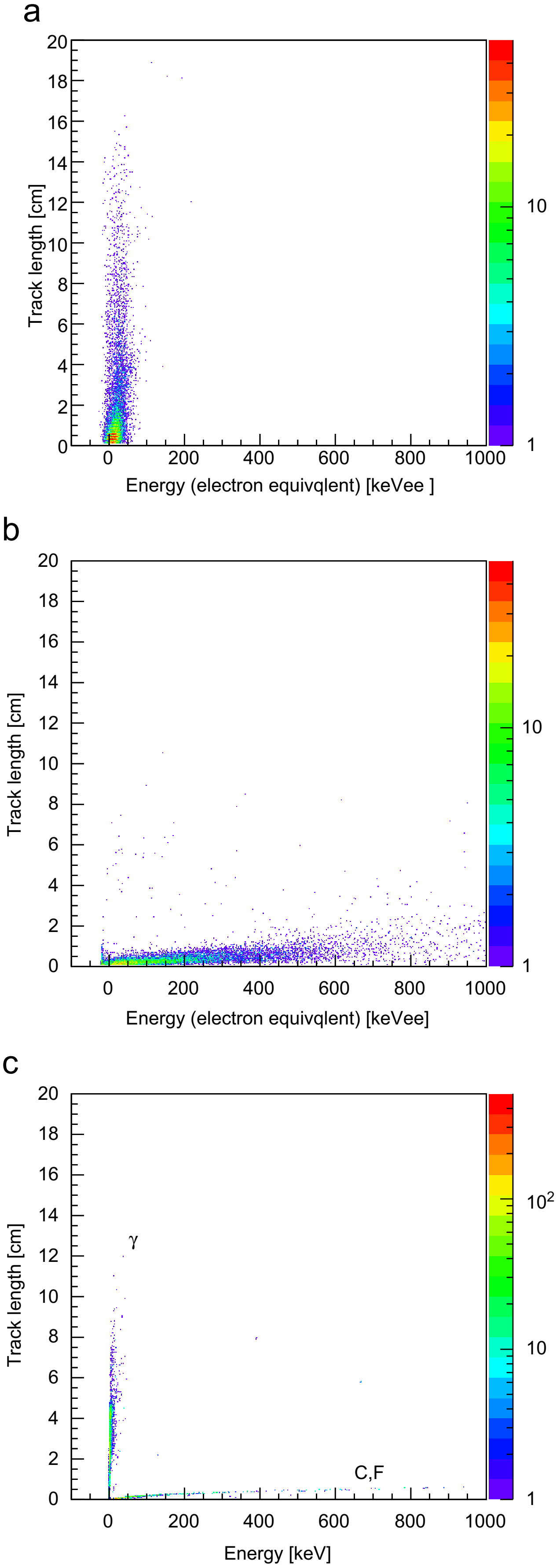

Fig. 4. Track length as a function of deposited energy with 150 Torr CF_4: (a) high-gain operation (low $\mathrm{d}E/\mathrm{d}x$ threshold); (b) low-gain operation (high $\mathrm{d}E/\mathrm{d}x$ threshold); (c) Geant4 MC simulation without consideration of the diffusion of drift process, the energy resolution, and the detection threshold.

900) is shown in Fig. 3. The MC (Geant4 [11]) simulated track length without consideration of the diffusion, the energy resolution, and the dE/dx threshold is also indicated for a comparison. The geometry used for the simulation was in accordance with Figs. 1 and 2, and the neutron energy spectrum of the spontaneous fissions of ^{252}Cf was assumed to be

$$\frac{dN}{dE} = \sqrt{E}\exp\left(-\frac{E}{T}\right) \quad (1)$$

where $T = 1.3\,\mathrm{MeV}$ [12].

Under operation with a gas gain of 3000, electron recoils and proton (of C_2H_6) recoils were clearly observed according to their dE/dx. On the other hand, in the operation of the gas gain of 900, the C and Ar recoils and some proton recoils were observed due to the high dE/dx threshold.

3.2. CF_4 150 Torr run

The drift cathode plane was supplied −2 kV, which gives a drift field of 120 V/cm and the electron drift speed of 12.0 cm/μs. The anode voltage of the μ-PIC was fixed at 600 V.

The measured track length of events when the GEM voltage was set to 215 V (gas gain of 4500) and 95 V (gas gain of 800) are shown in Fig. 4. The threshold voltage of the discriminator of the ASD chip was as high as 100 mV; therefore, only C and F recoils were clearly observed under operation with a gas gain of 800.

4. Discussion and prospects

We successfully showed the nuclear recoils in 150 Torr of $Ar-C_2H_6$ (90:10) and CF_4 gases according to their dE/dx by changing the detector threshold. The energy loss of protons became lower as the energy increased as opposed to the other nuclei [13]. Consequently, the proton band in Fig. 3(b) is truncated at the threshold set in the measurements, which corresponds to about 5 keV/400 μm. In terms of dE/dx, the tracks in the micro TPC were much easier to detect for C, F or Ar recoils.

Ultimately, our concern is the recoil direction of such nuclei below 100 keV to allow us to observe the signals of WIMPs. In order to obtain longer tracks and clear Bragg curves, higher gas gain operations at lower pressures with low-energy neutron beams are needed. The measurement of the incident neutron energy with Time-Of-Flight may also be useful to examine the quenching factor of nuclear ionization in the micro-TPC.

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