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Screening ultra-low alpha emissivity from the material surface based on a gaseous TPC with PMTs

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A gaseous time-projection chamber (TPC) based on a low-alpha emitting μ-PIC was developed to measure alpha emissivity from the surface of the material used in the detector such as searching dark matter and neutrinoless double beta decay events. The main background of the current screening is events with the radon emitting alpha particles. We plan to upgrade by installing photo-multiplier tubes (PMTs) to reduce radon background events. Low-pressure tetrafluoromethane gas which is filled in the TPC emits light simultaneously with the time when alpha deposits energy in the gas and the ionized electrons cascade on the anode electrode. The position along the drift direction for the alpha particle can be determined by detecting the first and second scintillation light. In this work, we measured the electron drift velocity as a function of the electric field, length, and gas pressure by the detection of these scintillation lights as the demonstration of discrimination with the alpha emission from the sample surface and radon. Then, we performed to evaluate the detection efficiency of the first scintillation light to be ~20% for a PMT and to measure the alpha emissivity of a sample as a demonstration using μ-PIC and PMTs.

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1. Introduction

The detectors for direct dark matter search require material including ultra-low radioactive impurities and massive target size. The several groups with massive liquid-xenon detectors lead to the search of the weakly interacting massive particle (WIMP) as a candidate of the dark matter directly and strongly constraint the WIMP-nucleon cross section for a WIMP mass of $O(10^0$–10^3 GeV$/c^2)$ [1–4]. Improving the sensitivity, they would soon reach the neutrino coherent scattering floor. Then, its signal cannot be identified whether WIMP.

A direction-sensitive direct WIMP search is a good solution to search beyond the neutrino floor. Recently, NEWAGE [5], DRIFT [6], DM-TPC [7], and CYGNUS/CYGNO [8] groups have been developing a time-projection chamber (TPC) based detectors. NEWAGE leads to search WIMP with three-dimensional tracking for nuclear recoil and derived the upper limit of spin-dependent WIMP-proton cross-section to be 50 pb for a WIMP mass of 100 GeV$/c^2$.

The main background of such WIMP-search detectors was that radon gas emanates from radioactive impurities in the device, and it needs to produce devices with fewer impurities. Therefore, it is important to measure the sample with ultra-low radioactivity background.

A low-pressure tetrafluoromethane (CF_4) gaseous TPC with μ-PIC [9, 10] has been conducted to measure the alpha emissivity from the sample surface for several experimental groups, in which the measurement was performed with the sensitivity of $O(10^{-3}\ \alpha/\mathrm{cm}^2/\mathrm{hr})$. The main background in the alpha emissivity measurement is events of alpha particles emitted from radon gas that emanated from the detector materials. We have been improving the sensitivity by suppressing the radon-induced alpha events, in addition to the replacement of low-impurities devices. Due to the drift length determination, it is discriminated that the events of alpha particles from whether radon or samples. In this work, a small-size PMT was added to the TPC, then 1st and 2nd scintillation lights in CF_4 gas were observed for verification. An electron drift velocity measurement based on scintillation light determination is a good demonstration to determine the position of alpha particle emission.

2. Alpha-particle imaging detector

The schematic view of the gaseous TPC is shown in Fig. 1. In the stainless steel vessel, CF_4 gas of 0.2 atmospheric pressure (atm) is filled and the detector based on a time-projection chamber which consists of μ-PIC, field cage, and drift plate is installed. The gas is circulated at ~300 cc/min to capture out gas such as oxygen and water vapor by active charcoal. The field cage with the size of $(34 \times 34) \times 15$ cm^3 makes a linearly electric field by surrounding the copper wires and chain resisters. Each plane of this cage has four view windows to detect scintillation light from the outside. The copper plate with the size of (34×34) cm^2 with 15×15 cm^2 window in the center (called the drift plate) is put on the top of the cage and connects to the chain resisters, then a high voltage O(kV) is applied to the drift plate (called V_{drift}).

A 13×13 cm^2 copper plate with ^{210}Po on the surface was used as the alpha source. The emissivity of alpha particles is $7.06 \pm 0.05\ \alpha/\mathrm{cm}^2/\mathrm{hr}$. The alpha source is put on the copper mesh covering the window of the drift plate. An alpha particle ionizes the electrons and light is emitted simultaneously (called S1). The electrons move toward the bottom with constant velocity by the electric field. A low-α μ-PIC [11] (produced by DNP) suppressed radioactive impurities than a standard μ-PIC is set on the bottom to detect the electrons. The effective area is 30×30 cm^2. The gas gain is a few hundred for applying 550 V. When the electrons arrive at the μ-PIC, the signals are produced in the anode and cathode. Then, light is emitted by the electron's avalanche amplification (called S2).

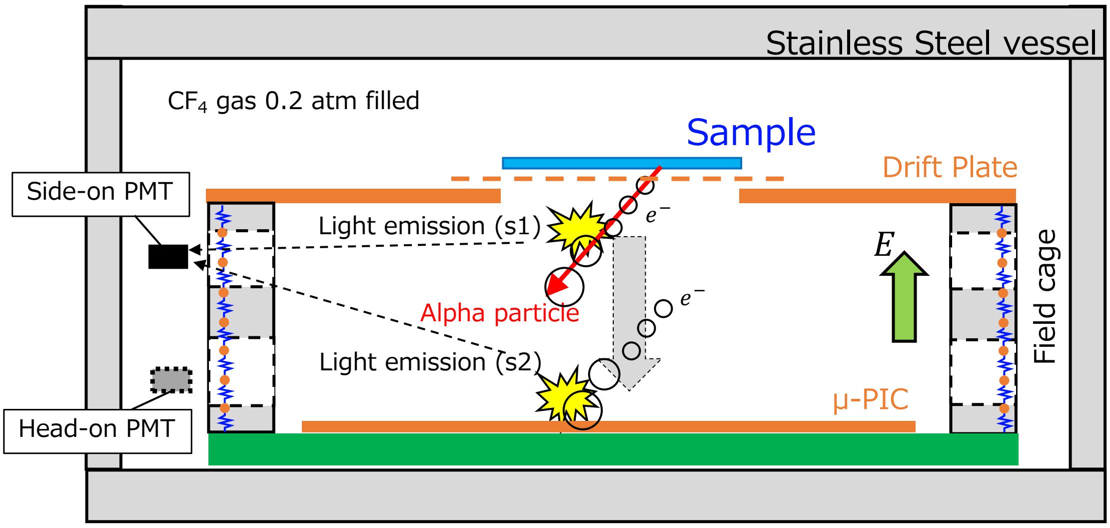

Figure 1: Schematic view of alpha imaging detector based on time-projection chamber with μ-PIC and photomultiplier tube (PMT).

In this work, we used two types of small-size PMTs. The mounting position of each PMT is shown in Fig. 1. A head-on type PMT (Hamamatsu, R9880U-210) with an 8-mm diameter cathode was installed between the vessel and the field cage. The photocathode faces toward center though the bottom window of the cage wall. It is used to measure an electron's drift velocity. A side-on type PMT (Hamamatsu, R6352) with a 4×13 mm^2 cathode was installed between the vessel and the field cage toward the center. The photocathode faces toward center though the top window of the cage wall. It is used to measure the S1 detection efficiency and estimate the alpha emissivity performance.

The light of S1 and S2 is observed by the PMT through the window of the side plane of the field cage. The PMTs are operated at a gain of $\sim 10^7$. The data of waveform signals of the sum strips of μ-PIC and the PMT are recorded by a flash ADC (REPIC, RPV-160) with a 100 MHz sampling rate.

3. Data taking

We have taken data as follows. (1) measurement of the electron drift velocity, (2) measurement of the S1 detection efficiency, (3) background measurement with the copper mesh for sample, and (4) background measurement without the copper mesh. These runs are summarized in Table 1.

The gas pressure is monitored by the capacitance gauge (CANNON ANNELVA, M-340DG-13/N25) and has controlled within 1.5% for 0.21 atm in this work. The room temperature is kept to 24–26 °C and monitored during these runs.

Table 1: Run Summary.

Run#	Purpose	Modifications	Used PMT	Measuring period
1	The drift velocity	Drift voltage from 0.4 to 2.4 kV	R9880U-210	One month
2	The S1 efficiency		R6352	One month
3	Background	w.o. α source	R6352	Thee months
4	Background	w.o. α source and the mesh	R6352	One month

4. Analysis

Figure 2 shows typical waveforms for alpha-particle events in V_{drift}=2.0 kV. This figure shows these waveforms of μ-PIC and PMT by shifting 0 mV and −20 mV, respectively. It was found the signal of μ-PIC and the S2 signal is synchronous. The S1 signal appeared around 1.5 μs before the S2 signal.

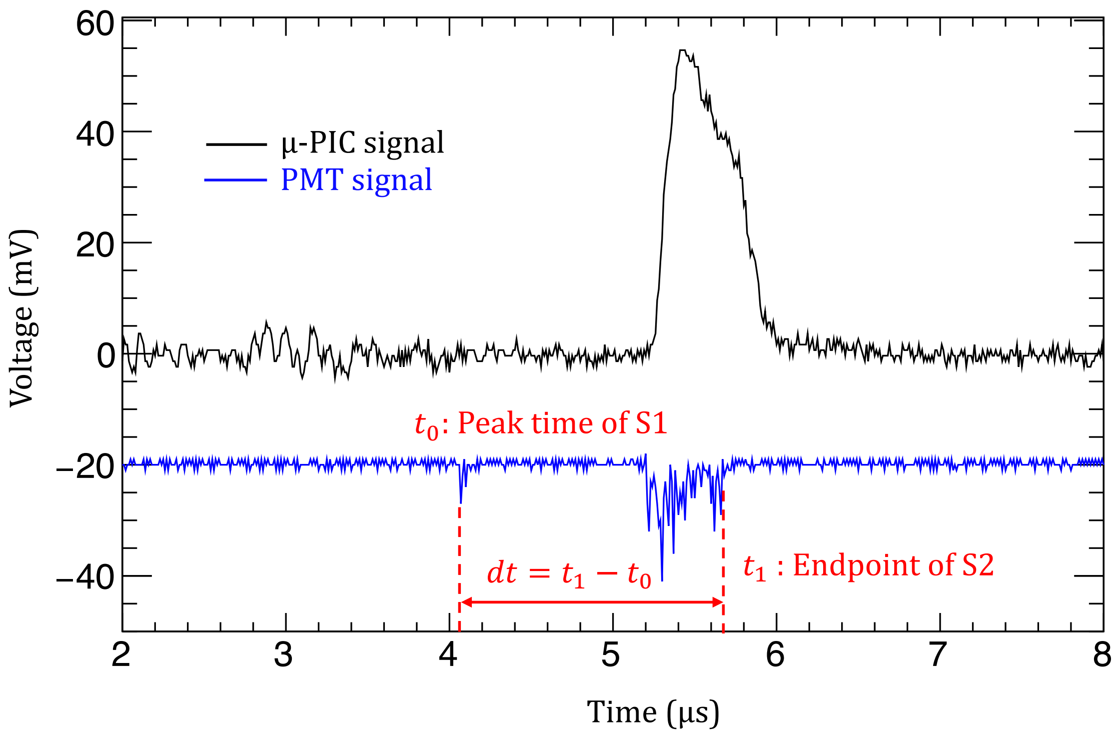

Figure 2: Typical waveform of μ-PIC cathode sum signal and PMT anode signal for an event of alpha emitted from the source.

In the waveform analysis, the peak time and height of the S1 signal were searched in 3 to 5 μs region. For the S2 signal, the charge was integrated with 5 to 6.5 μs region, and the endpoint was recorded as shown in Fig.2. The pedestal height and charge as accidental events are calculated in 0 to 2 μs region.

A time interval ($dt = t_1 - t_0$) between the peak time of the S1 signal (t_0) and the end time of the S2 signal (t_1) is calculated for the events observed in both signals of S1 and S2. The end time was chosen because of the constant drift distance for electrons on top position even if alpha particles emit any direction. The distance (L) between μ-PIC and the drift plate is a constant of 15 cm. The velocity is calculated as L/dt, e.g. in the case of V_{drift}=2.0 kV, the mean dt is determined to be 1.641 ± 0.002 μs by the Gaussian fit around the peak region, where the error indicates a sigma of the fit. The velocity is calculated to be 9.14 ± 0.01 cm/μs. In the same way for other V_{drift}, the velocities have been determined.

For the run of the drift velocity measurement, E/P (kV/cm/atm) was calculated to compare the simulation, Magboltz [12], which solves the Boltzmann transport equations to calculate the transport properties of electrons in the gas. The gas pressure was also a constant of 0.21 atm. The applied voltage was changed E/P from 0.762 to 0.127.

Alpha particle's events are characterized as a profile of track and energy deposit, then the direction of upward- or downward-like can be determined by the μ-PIC's signal waveform [9]. The net alpha emissivity would be estimated by subtracting upward- and downward-like in the sample area. In this work, for the screening, we selected the data samples that the top position of an alpha particle is within the 15×15 cm^2 window in the center.

5. Results

5.1 Electron's drift velocity

The electron drift velocity was determined as a function of E/P in low-pressure CF_4 gas as shown in Fig. 3. This result is reasonable compared to previous measurements in a case of gas pressure at 1 atm and a good consistency with the Magboltz simulation [12].

5.2 S1 detection efficiency

Figure 4 shows distributions of the pulse height of S1 signal for two type PMTs. The detection efficiency is defined as a ratio of events that the pulse height of the S1 signal is over each threshold to all. Taking into account its accidental background distribution, the threshold is determined to be 3 mV for head-on type and 10 mV for side-on type PMT. The efficiencies are determined to be ~5% and ~20% for the head-on and the side-on type PMTs, respectively.

5.3 Surface alpha emissivity demonstration

Figure 5 (a)/(b) shows the distributions of the time interval dt to compare with upward- and downward-like events for w./w.o. mesh. The finite excess was significantly found at 1.6 μs at run 3 (w. mesh), where the time interval corresponds to the same distance from the drift plate to μ-PIC cathode. The alpha emissivity was roughly estimated to be $\sim 10^{-2}$ α/cm^2/hr for $E_\alpha > 2.5$ MeV[1]. On the other hand, at run 4 (w.o mesh), the downward-like events are consistent with the upward-like. It indicates emitting alpha particles from the surface of the mesh and becomes a good demonstration for sample screening.

[1] E_α indicates the energy of alpha particle equivalent.

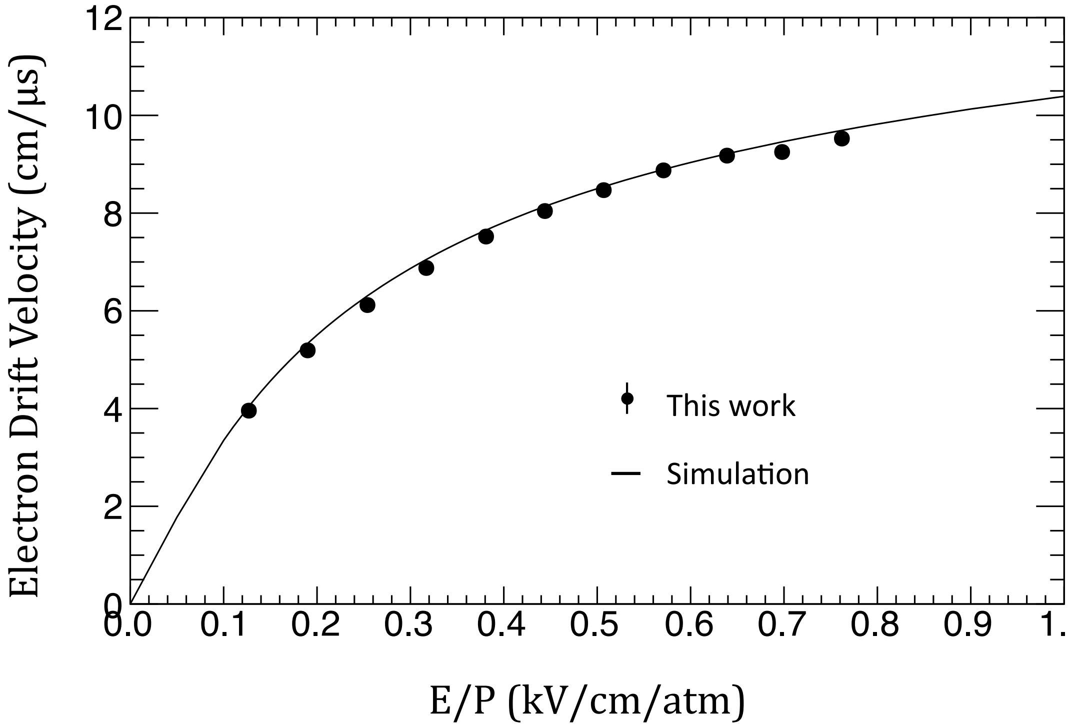

Figure 3: Electron drift velocity as a function of the electric field per length per pressure (E/P) in CF_4 gas for this work in comparison with the simulation.

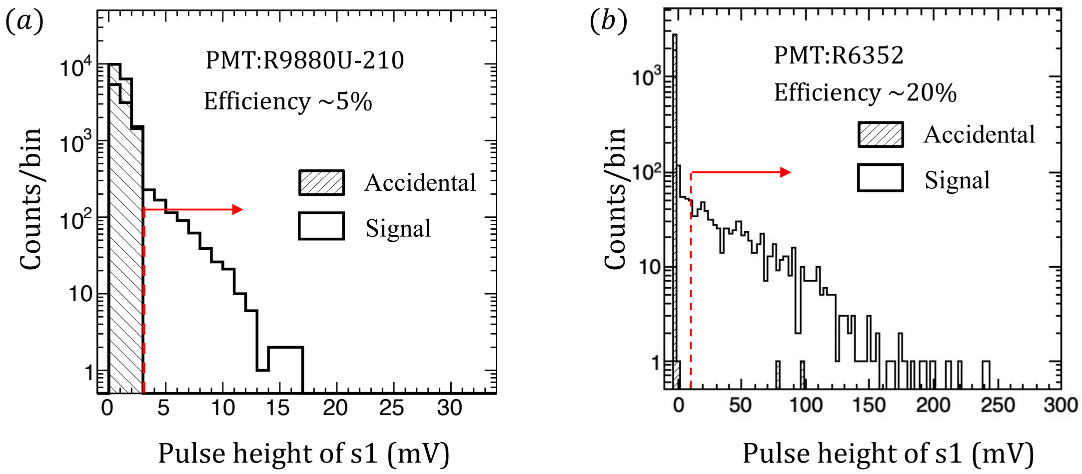

Figure 4: Pulse height distributions of S1 signal and accidental using (a) head-on type R9880U-210 and (b) side-on type R6352 PMTs. Red dashed lines are these threshold to determine the S1 detection efficiency.

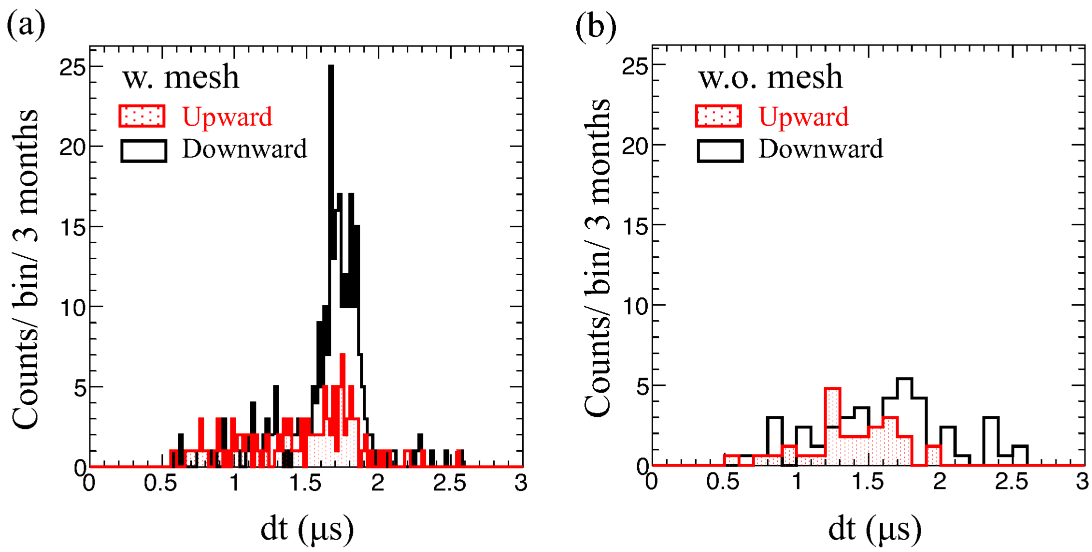

Figure 5: Timing distributions comparing with upward- (red) and downward-like (black) events for w. (a) and w.o. mesh (b), respectively. Note that the livetime of run w. mesh is 3 times longer than w.o. mesh.

6. Discussion

We discuss realizing the sensitivity improvement for the TPC by installing PMTs. To improve the S1 efficiency, the photo coverage size should be extended, e.g. adding PMTs. In this work, the efficiency is determined to be ~20% by the side-on type PMT. Based on the result of the S1 detection efficiency with the use of single PMT, we estimate the expected efficiencies of 41%, 61%, 88%, and 96% for using 2, 4, 8, and 12 PMTs, respectively. The position dependence of the efficiency should be taken into account, but these are estimated roughly in an assumption of no dependence.

On the other hand, it should be taken into account for the radioactive impurities in the PMTs even if alpha-particle events for the emanation of radon gas from these materials can be also eliminated. We measured radioisotopes for the PMTs by an HPGe detector and the alpha-particle emissivity from the PMTs by the TPC's own. It was found the side-on type PMT (R6352) has 60 ± 8 mBq of ^{238}U upper stream, 106 ± 4 mBq of ^{238}U middle stream, and 18 ± 1 mBq of ^{232}Th, and a finite alpha emissivity of $0.124 \pm 0.027\ \alpha/\mathrm{cm}^2/\mathrm{hr}$ for $E_\alpha > 2.5$ MeV.

Therefore, the number of PMTs which are installed in the TPC should be optimized in consideration of a trade-off between the background radioactivity and the S1 detection efficiency. In prospect, in addition to the S1 sensitivity increase, we will install ultra-pure devices (e.g. μ-PIC with lower impurities) in the TPC in order to improve the sensitivity to less than $O(10^{-4}\ \alpha/\mathrm{cm}^2/\mathrm{hr})$.

7. Summary

We have been developing a gaseous time-projection chamber using μ-PIC and PMT to measure the alpha emissivity of the material surface. It contributes to the material selection for dark matter detectors. We have demonstrated as follows. The S1 and S2 lights are observed clearly. The electron drift velocity as a function of the electric field per length per gas pressure is also determined and is consistent with the simulation. The alpha emissivity from the mesh is measured in long-term operation. The detection method would lead to a precise measurement of alpha emissivity in the next generation.

Acknowledgements

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