Development of Dual-phase Liquid Xenon TPC with a Hermetic Quartz Chamber

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An idea of a hermetic quartz chamber to be installed in a dual-phase xenon time projection chamber (TPC) is useful to improve a future direct dark matter search. The hermetic chamber made of quartz can separate TPC’s sensitive volume from an outside environment to prevent contamination by radioactive impurities and electronegative impurities that emanate from detector materials, which increase the radioactive background and degrade ionized electron lifetime, respectively. We developed a TPC with a quartz chamber that contains a \( \phi 48 \times 58 \text{ mm} \) liquid xenon TPC at Kamioka Observatory, Japan, and successfully observed a single-electron peak demonstrating the proof of principle. In this article, we report the basic property of the TPC with a quartz chamber such as light and ionization yield signals.

Subject Index dark matter, liquid xenon, low background

1. Introduction

Weakly interacting massive particles (WIMPs) are hypothetical particles, which are present in the universe, and are cold dark matter candidates; the experiments to directly observe WIMPs via elastic scattering via nuclear recoil of its target materials are ongoing or have been proposed (see [1–5]). Among these experiments, liquid noble gas (e.g., liquid xenon (LXe) and liquid argon (LAr)) experiments are leading in this field and giving the most sensitive WIMP-nucleus elastic cross-sections. The direct search using nuclear recoil with low energy (\(< 100 \text{ keV}\)) is limited by the radioactive background caused by radon emanation from detector materials as well as by the energy threshold of the detectors. The identification

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of nuclear recoil signal from electron recoil owing to the background $\gamma$ or $\beta$ rays and a large target mass are considerable advantage for the search. Therefore, time projection chambers (TPCs) containing dual phase Xe or Ar (i.e., consisting of liquid and gas) have been successful and aiming a WIMP–nucleus spin-independent elastic cross-section of $10^{-48}$ cm$^2$. For the next generation of dark matter experiments, it is essential to further reduce radioactive radon gas contamination [2–5].

Recently, a prototype dual phase Xe detector with a hermetic quartz chamber was constructed and tested at Kamioka Observatory in Japan. The purpose of a quartz chamber is to separate its sensitive volume from the outside environment to prevent contamination from both radioactive and electronegative impurities that emanate from detector materials (e.g., PMTs, electrode, and cables), which increase radioactive background and degrade ionized electron lifetime, respectively.

In the past, a hermetic TPC was constructed for an R&D program by the Waseda group [6] and for a dark matter search program of the XMASS experiment [7] at Kamioka in early 2000s. Gas and liquid xenon were surrounded by PTFE cones and two MgF$_2$ windows in a stainless steel or a copper vessel. Two photomultipliers (PMTs) were coupled to these windows through a 1-mm-thick vacuum. The loss of scintillation light collection from LXe in this vacuum and window interface was unavoidable. Another hermetic design with dual phase xenon was proposed by the XAX experiment in 2009 [9]. The objective of the XAX experiment was to produce a multi-ton, multi-target detection system with a hermetic acrylic vessel with a wavelength shifter inside the wall that holds LXe or LAr XAX detector. Of note, the possibility of using ultrapure LXe as a low energy solar neutrino, neutrinoless double beta decay, and WIMP dark matter search was originally discussed well before this proposal with a 10-ton single phase detector in [8].

However, none of these experiments proposes a design to realize a low level of radioactive radon or reduce electronegative contamination inside TPC. In fact, the main challenge is to achieve the amount of $^{222}$Rn of 1 $\mu$Bq/kg or less, which is similar to the event rate of pp solar neutrino at low energy, to obtain the sensitivity of a $10^{-48}$ cm$^2$ or lower WIMP-nucleon cross-section. Quartz is known to have a small concentration of radium [10]. Thus, it emits negligible amount of radon. In addition, in the future detector, the drift length of TPC is proposed to be approximately 1.5 m or more, which requires the ionized-electron lifetime to be 1 msec or more to avoid the deficit of charge signal [5].

A hermetic TPC made of quartz is advantageous for future large detectors and for a low-mass WIMP search by, so called, the S2-only analysis [11–14]. It is possible to avoid the secondary electron emission caused by VUV scintillation light of liquid xenon (7 eV) owing to quartz’s large band gap of approximately 9 eV [15]. In addition, the quartz chamber will also prevent drift electrons that are generated in gas from entering the sensitive volume. These electrons produce noise events with small S2 signals and act as backgrounds for the sub-GeV dark matter search [12, 14]. Thus, a quartz chamber will help search for WIMPs with a GeV–TeV mass and for other dark matter candidates with sub-GeV masses.

It is necessary to confirm that the TPC works normally even with the quartz chamber. In addition, a sensitivity for small signals should be studied because that is an important property for the sub-GeV dark matter search. In this paper, we report the basic properties of the prototype TPC with the quartz chamber such as light yield and ionization yield signals, and check the abovementioned issues. Though the prototype was not hermetically sealed,
its design followed the concept of the hermetic TPC. The demonstration of the protection performance against radon and electronegative impurities will be the subject of future work. The detector apparatus is explained in Section 2, and the methodology to measure signals using TPC is described in Section 3. The results and conclusion are described in Sections 4 and 5, respectively.

2. Apparatus

Figure 1(a) shows the image of the prototype TPC, which consisted of a quartz chamber, electrodes that were attached inside and around the chamber, and photomultipliers (PMTs). The quartz chamber consisted of two 5-mm-thick plates, a 5-mm-thick outer wall, a 2.5-mm-thick inner wall made of ES-grade quartz, and PTFE support structures that filled the gaps between these quartz components. The chamber had a $\phi 48 \times 63$ mm cylindrical-shaped inner volume. Each top and bottom plate had a $\phi 3$ mm hole for passing xenon to purify the inner volume. The geometry of the chamber is shown in Fig. 1(b).

Anode and cathode electrodes were attached to the inner surfaces of the top and bottom quartz plates, respectively, by pushing with the PTFE support structure. These electrodes were chemically-etched square grids that were made from 0.1-mm-thick stainless-steel sheets. The grid spacing was 2 mm, and the width of the grid bars was 0.1 mm. A gate electrode was a plane that was formed by wires arranged in parallel with a 2-mm spacing. The electrode was placed 5 mm below the anode electrodes. The wire was a $\phi 0.1$-mm gold-plated stainless steel. High voltages of typically $+2250$, $-2250$, and $-2750$ V were applied to anode, gate, and cathode electrodes, respectively, to create a downward electric field. To arrange the electric field uniform and in parallel, four stainless steel field-shaping rings with a $5 \times 5$ mm$^2$ square cross-section were equally spaced between the gate and cathode electrodes. Each of them including the gate and cathode electrodes were connected in series with 100-MΩ resistors. Two wire planes that were grounded to 0 V were attached to the outer surfaces of the top and bottom quartz plates to prevent electric field from leaking outside the chamber.

The inner volume was soaked in LXe. The liquid surface level was adjusted to be 2 mm below the anode. The liquid level was monitored by a capacitance level sensor mounted next to the quartz outer wall.

When a charged particle deposits its energy in the LXe region, a part of the energy is used for excitation and ionization of xenon atoms. Scintillation photons (S1) are produced via de-excitation or recombination processes [16], while a part of electrons generated by ionization are drifted upward by the cathode–gate field and then produce secondary scintillation (S2) owing to the strong gate–anode field. To detect S1 and S2 scintillations, two PMTs (HAMAMATSU R10789) were placed below and above the top and bottom quartz plates, respectively.

Signal pulses from PMTs were recorded by a 1-GHz sampling 10-bit ADC waveform digitizer CAEN v1751. The data acquisition trigger was made by the coincidence of the top and bottom PMT pulses, and waveforms in the range from $-8$ to 192 $\mu$sec around the trigger timing were stored for every event. The PMT gain was monitored by measuring a single photoelectron (PE) produced by a blue LED which was installed next to the quartz outer wall.

The TPC was placed inside a vessel containing LXe, which consisted of a SUS304 ICF152-standard nipple, as shown in Fig. 1(c). The upper edge of the LXe vessel was connected
to a refrigerator to maintain the temperature around the top (bottom) PMT at $-100 \, ^\circ C$ ($-94 \, ^\circ C$) and the gauge pressure inside the vessel at 0.07 MPa. The outer vacuum vessel surrounded the LXe vessel for heat insulation. The vacuum vessel had a pit to put an 80-kBq $^{57}$Co source. The source was placed 9 cm away from the TPC center axis and 1 cm above the cathode electrode to irradiate 122-keV $\gamma$ toward the entire TPC.

Owing to the existence of electronegative impurities (e.g., $O_2$), a part of drift electrons is absorbed before reaching the gate electrode and the S2 signal is strongly attenuated. Therefore, the circulation system was installed to purify xenon. The LXe vessel had two gas ports to install and extract xenon gas. The gas extracted by a pump at a flow speed of 10 L/min was passed through a getter purifier to remove impurities and is then returned into the LXe vessel. A heat exchanger [17], which exchanges heat between inward and outward gas flow, stabilized the circulation. The strong attenuation of S2 signals observed at the beginning was resolved by the circulation, as shown in Fig. 2(a). We evaluated the lifetime $t_{\text{att}}$ of the drift electron by fitting with the equation:

$$PE_{S2}(t_{\text{drift}}) = PE_{S2}(t_{\text{drift}} = 0) \times \exp\left(-\frac{t_{\text{drift}}}{t_{\text{att}}}\right),$$

where $PE_{S2}$ and $t_{\text{drift}}$ are the charge and the drift time of S2 signal, respectively; its definition will be described in Section 3.1. After 100 hours of circulation, we achieved $t_{\text{att}} > 200 \, \mu$sec as shown in Fig. 2(b). The data with $t_{\text{att}} > 200 \, \mu$sec was used for the following analysis.

3. Analysis
To study the basic performance of the TPC, we observed S1 and S2 signals, which originated from a 122-keV $\gamma$ from the $^{57}$Co source.
Fig. 2: (a) S2 signal attenuation depending on the drift time after a 237-hour circulation. The black points with error bars show peak value of each time bin. The solid line shows a fit result with Eq. (1). (b) Electron lifetime $t_{att}$ as a function of circulation time.

3.1. Definition of S1 and S2 signals

Typically observed waveforms are shown in Fig. 3. The top PMT was operated with a higher voltage, 1275 V, to observe 1 PE (therefore, the S2 signal usually was outside the ADC range), while the bottom PMT voltage was lower, 1000 V, to record the S2 signal without saturation. The timing of S1 signals $t_S1$ was fixed, at $t_S1 = 7.9 \, \mu\text{sec}$, because the data acquisition trigger was made by S1 coincidence of the top and bottom PMTs. We evaluated the S1 charge $PE_{S1}$ by integrating a waveform in the 7.8–8.15 $\mu\text{sec}$ region and converting it to the number of PE via the multiplication by a correction factor $C_{Q\rightarrow PE}[\text{PE/(mV} \cdot \text{nsec)}] = 1/142$ (top PMT) or 1.08 (bottom PMT), which was derived by monitoring 1-PE pulses induced by the LED. To search for S2 pulses, we performed a simple peak finding approach, where the peak was defined as a waveform sampling point with ADC values exceeding 10 mV and being higher than the previous and next sampling points. If two peaks were located within 1.5 $\mu\text{sec}$ of each other, the lower one was discarded. For each peak, the S2 signal charge $PE_{S2}$ was calculated as an integral of ADC values around $\pm 1.5 \, \mu\text{sec}$ of the peak multiplied by $C_{Q\rightarrow PE}$, and the S2 timing $t_S2$ was determined as a weighted mean in the integral range. Then, the drift time of S2 $t_{drift}$ was determined as $t_{drift} \equiv t_S2 - t_S1$.

3.2. $^{57}$Co selection

Figure 4(a) shows the observed $PE_{S1}$ distribution. It has a clear peak from a 122-keV $\gamma$-s from the $^{57}$Co source. To select the $^{57}$Co events, we required

$$\sqrt{\left(\frac{(PE_{S1}^{top} - \langle PE_{S1}^{top}\rangle)}{\sigma_{S1}^{top}}\right)^2 + \left(\frac{(PE_{S1}^{bot} - \langle PE_{S1}^{bot}\rangle)}{\sigma_{S1}^{bot}}\right)^2} < 2,$$

(2)
where the superscript top (bot) represents the quantity measured in top (bottom) PMT, and $\langle PE_{S1}\rangle$ and $\sigma$ are the mean and width of the $PE_{S1}$ distribution evaluated using a Gaussian fit, respectively. The selected region is illustrated in Fig. 4(b).

The observed $S2$ peaks described in Section 3.1 frequently included noise or $S1$ afterpulses. For the $S2$ signal observed in the bottom PMT, the height had to be $> 30$ mV, the drift time $t_{\text{drift}}$ had to be $> 0.3$ $\mu$sec to distinguish from $S1$ afterpulses, and a ratio of charge to height had to be $> 150[\text{[nsec]} \times Q_{bot}^{\text{PE}}].$ In addition, we required that the top PMT had an $S2$ signal with an overflown peak height within 1 $\mu$sec around the bottom PMT $S2.$
event where only one S2 signal satisfies these requirements was regarded as the $^{57}$Co event and used for analysis. Figure 4(c) shows the S2 PE distributions before and after the $^{57}$Co selection.

4. Results

4.1. Energy distribution

With a finite cathode–gate voltage difference $\Delta V_{CG}$, a part of ionized electrons drifts to produce the S2 signal, while the rest of ionized electrons undergo recombination before drifting, and contribute to the S1 signal. Stronger $\Delta V_{CG}$ produces more drifting electrons, i.e., more $PE_{S2}$ and less $PE_{S1}$.

We measured $PE_{S1}$ and $PE_{S2}$ distributions with various $\Delta V_{CG}$. As shown in Fig. 4, the $^{57}$Co peak was observed in both $PE_{S1}$ and $PE_{S2}$ distributions. The peak positions were evaluated with a Gaussian fit and are shown in Fig. 5 as a function of $\Delta V_{CG}$. The S1 (S2) charge showed a negative (positive) dependence on $\Delta V_{CG}$, as qualitatively expected for the TPC. Quantitative discussion is still difficult because the electric field had a non-uniformity, especially at low $\Delta V_{CG}$. A detailed simulation, which considers the effect of non-uniformity, is currently being prepared.

![Fig. 5: $PE_{S1}$ (blue) and $PE_{S2}$ (red) of $^{57}$Co events as a function of the cathode–gate voltage difference $\Delta V_{CG}$. Marker difference indicates different voltage settings. The circles represent the data acquired with the anode voltage of 2250 and the gate voltage of $-2250 \text{ V}$, while in the data shown in the triangles was acquired at the anode voltage of 2250 and the gate voltage of $-1000 \text{ V}$.](image)

4.2. Drift time distribution

We measured the $t_{\text{drift}}$ distribution with the setting of anode voltage of 2250 V, gate voltage of $-2250 \text{ V}$, and cathode voltage of $-2750 \text{ V}$, as shown in the black histogram in Fig. 6(a). The expected drift time from the cathode to the liquid surface was calculated to be $41.3 \mu\text{sec}$ using the COMSOL simulation [18] and the literature data of drift velocity [19]. The end point of the observed $t_{\text{drift}}$ distribution is consistent with this expectation. Some dips were
observed in the $t_{\text{drift}}$ distribution. On the basis of the Monte Carlo (MC) study, the dips are attributed to the field-shaping rings that prevent $^{57}\text{Co} \gamma$s from entering the sensitive volume. The positions of the dips could be roughly reproduced by the Geant4 toy simulation.

In addition, we acquired data while changing $\Delta V_{CG}$ from 58 V to 2 kV, as shown by the different colors in Fig. 6(a). We evaluated the width of the $t_{\text{drift}}$ distribution as $t_{99\%}$ which satisfies

$$
\frac{\int_{t_{99\%}}^{t_0} f'(t_{\text{drift}})dt'_{\text{drift}}}{\int_{t_0}^{t_{99\%}} f(t_{\text{drift}})dt_{\text{drift}}} = 99\%,
$$

where $f(t_{\text{drift}})$ represents the observed $t_{\text{drift}}$ distribution. The $t_{99\%}$ shows the positive dependence on $\Delta V_{CG}$ as shown in Fig. 6(b). This is consistent with a qualitative expectation that drift velocity becomes faster with a stronger drift field.

The quantitative evaluation of the drift velocity has not been performed yet owing to the non-uniformity and distortion of the electric field. A detailed simulation for drifting electrons is under preparation.

**Fig. 6:** (a) Drift time $t_{\text{drift}}$ distribution. Color difference indicates different voltage settings, as described in the plot. (b) Width of $t_{\text{drift}}$ distribution, $t_{99\%}$, as a function of $\Delta V_{CG}$. The definition of $t_{99\%}$ is written in the text. The meaning of marker difference is the same as Fig. 5.

**4.3. Single electron sensitivity**

To explore sub-GeV dark matter using the S2-only analysis, a sensitivity for a small S2 signal is desirable. Thus, we tried to observe the S2 signal at low energy limit (i.e., the S2 signal produced by a single drift electron). S2 photons induced by $^{57}\text{Co} \gamma$s are a good source of single drift electrons. These photons have a 7-eV energy, which is sufficient to produce
a single electron via the photo-electric effect on the detector material surface or via photo-
ionization with impurities in xenon (e.g., $O_2^-$). Thus, small S2 signals originated from single
drift electrons are expected to appear after the large $^{57}$Co S2 pulse. Actually we observed
clustered photoelectron peaks after the $^{57}$Co S2 as shown in Fig. 7(a). Figure 7(b) shows
the PE vs. timing distribution of such clusters, where two components are observed. From
its timing distribution, we considered that the component with $\sim 17$ PE around 30–45 $\mu$sec
after $^{57}$Co S2 was attributed to S2 from single drift electrons. The timing distribution of
clusters with $> 10$ PE is shown in Fig. 7(c). The distribution expands up to $t_{end} = 42.0$ $\mu$sec
and exhibits a peak. The $t_{end}$ was interpreted as the drift time from the cathode position
because $t_{end}$ is consistent with the width of the $t_{drift}$ distribution shown in Fig. 6(a) where
the black histogram shows the data taken with the same voltage setting as this single electron
study. Because the cathode electrode is a metal, many electrons are produced there via the
photoelectric effect compared to that at other surface of the inner volume, which resulted in a
peak for the drift time from the cathode. The large number of 1-PE pulses were accompanied
after $^{57}$Co S2, and the component with a few PE seems to come from such pulses which were
accidentally clustered. The origin of the 1-PE pulses is uncertain. This phenomena was also
observed in other groups [20, 21] and a possibility of a photon emission from PTFE by the
LXe VUV scintillation light was discussed there. In the $< 25$ $\mu$sec region, the separation of
these two components was worse because the PMT had an undershoot after the large $^{57}$Co
S2, and its gain temporarily decreased. We evaluated the PE distribution in the 30–50 $\mu$sec
region to avoid the undershoot region, and found that a peak of single drift electron is at
$PE = 17.2$, as shown in Fig. 7(d).

5. Conclusion

A reduction in radioactive radon and electronegative impurities emanated from detector
materials is a critical issue to improve future direct dark matter search using xenon TPC.
The use of hermetic quartz chamber in a TPC solves the abovementioned problems.

We developed a small prototype of TPC with a quartz chamber and successfully operated.
The measured PE distribution of S1 and S2, and the drift time distribution were correlated
with the drift field voltage strength, which was consistent with a qualitative expectation for
general TPC. In addition, we showed that the TPC can detect small S2 signals produced by
single drift electrons with a light yield of 17 PE per drift electron.

Thus, we confirmed that the TPC with a quartz chamber worked successfully as a xenon
TPC and has a sufficient light yield to observe a single drift electron. Currently, the results
are still qualitative, but a detailed simulation of drifting electrons is being prepared for the
quantitative evaluation. This result serves as a basis for the further R&D to demonstrate
the contamination reduction of radon and electronegative impurities.

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Research (ICRR), the University of Tokyo.
Fig. 7: (a) Cluster observed in the waveform, which is a candidate for the S2 signal from a single drift electron. In this event, we found 4 clusters with > 10 PEs. An enlarged view of the region of 87–89 µsec is shown in the right upper box. (b) PE vs. timing difference from $^{57}$Co S2 of the cluster. (c) Timing difference distribution of clusters with > 10 PE. (d) PE distribution in the timing difference between 30–50 µsec. The green line shows a convolution of Gaussian and Poisson distribution, and the blue line shows an exponential function. The red line shows the sum of the green and blue functions, which was used as a fitting function to evaluate the single drift electron peak.

References

[1] K. Abe et al. (XMASS Collaboration), Phys. Lett. B, 789, 45 (2019).
[2] B.J. Mount et al. (LZ Collaboration), arXiv:1703.09144 [physics.ins-det].
[3] E. Aprile et al., (XENON Collaboration), J. Cosmol. Astropart. Phys. 04, 027, (2016).
[4] C.E. Aalseth et al. (DarkSide Collaboration), Eur. Phys. J. Plus, 133, 131 (2018).
[5] J. Aalbers et al., J. Cosmol. Astropart. Phys. 11, 017 (2016).
[6] M. Yamashita, T. Doke, J. Kikuchi, S. Suzuki, Astropart. Phys. 20, 79, (2003).
[7] M. Yamashita, Technique and Application of Xenon Detectors, World Scientific (2002) p.136
[8] Y. Suzuki et al., arXiv:hep-ph/0008296v1.
[9] K. Arisaka et al., Astropart. Phys. 31, 63, (2009).
[10] K. Abe et al. (XMASS Collaboration), Nucl. Instr. Meth. A, 922, 171 (2019).
[11] J. Angle et al., (XENON10 Collaboration), Phys. Rev. Lett., 107, 051301 (2011).
[12] E. Aprile et al. (XENON100 Collaboration), J. Phys. G, 41, 035201 (2014).
[13] P. Agnes et al. (DarkSide Collaboration), Phys. Rev. Lett., 121, 081307 (2018).
[14] E. Aprile et al. (XENON100 Collaboration), arXiv:1907.11485 [hep-ex].
[15] E. Vella et al., Phys. Rev. B, 83, 174201 (2011).
[16] A. Hitach, Astropart. Phys. 24, 247, (2005).
[17] K.L. Giboni et al. J. Instrum. 6, P03002, (2014).
[18] COMSOL Multiphysics® www.comsol.com. COMSOL AB, Stockholm, Sweden.
[19] L.S. Miller, S. Howe, W.E. Spear, Phys. Rev., 166, 871 (1968).
[20] D.S. Akerib et al., arXiv:1907.06272 [astro-ph.CO].
[21] P. Sorensen and K. Kamdin, J. Instrum. 13, P02032, (2018).