Development of a Sealed Liquid Xenon Time Projection Chamber with a Graphene-Coated Electrode

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ABSTRACT: The liquid xenon (LXe) time projection chamber (TPC) technology is leading the dark matter direct detection in a wide range of dark matter masses from sub-GeV to a few TeV. To further improve its sensitivity to sub-GeV dark matter and its application in reactor neutrino monitoring via coherent elastic neutrino-nucleus scattering (CEνNS), more understanding and suppression of single/few electrons background rate are needed. Here we report on the design and performance of a sealed LXeTPC with a graphene-coated fused silica window as the cathode. The purpose of the sealed TPC is for isolating the liquid xenon target volume from the majority of out-gassing materials in the detector vessel, thus improving the liquid xenon purification efficiency and reducing the impurity-induced single/few electrons background. We investigated the out-gassing rate and purification efficiency using the data from the sealed TPC with a simple purification model. The single electron signals from the photoionization of impurities in LXe are obtained and their correlation with the LXe purity is investigated. The photo-electron emission rate on the graphene-coated electrode is compared to that from stainless steel, the electrode material typically used in LXe detectors. We discuss the possible further improvement and potential applications of the sealed TPC for the next generation liquid xenon experiments for dark matter and neutrino physics.

KEYWORDS: Dark Matter, Weakly Interacting Massive Particles (WIMPs), Liquid Xenon Time Projection Chamber (LXeTPC), Sealed TPC, Graphene-Coated, Electrode

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1 Introduction

The technology of Liquid Xenon Time Projection Chamber (LXeTPC) is widely used in rare event searches, such as direct detection of dark matter (DM) [1–3] and neutrino experiment [4]. The LXeTPC-based detectors are leading the searches for DM in form of weakly interacting massive particles (WIMPs) with masses above a few GeV [1]. LXe and also liquid argon (LAr) detectors have been used to search for sub-GeV DM via their scattering on electrons [5–8], but further improvement on sensitivity requiring more understanding and suppression of background at single and a few electrons level. A low background and single-electron sensitive LXe detector also has potential applications to detect coherent elastic neutrino-nucleus scattering (CEνNS) from reactor or solar neutrinos [9].

The LXeTPC detects primary scintillation signals (S1) in liquid xenon. The ionized electrons are drifting into the gas phase from the liquid xenon, where electroluminescence is produced under a strong electric field (~ 10 kV/cm), called proportional scintillation light (S2). Both S1 and S2 are recorded by photomultiplier tubes (PMTs). The z coordinate of the interaction can be extracted from time difference between S1 and S2, while the (x, y) coordinates can be reconstructed from the light pattern of S2 signal on top PMT array. The S2/S1 ratio is used to discriminate between nuclear and electronic recoils for background reduction. Benefits from the amplification of S2 signals, this technology can detect very low energy events in a few electrons level [7]. However, the background rate at single/few electrons level is still the limiting factor to improve the sensitivity. Photoionization on metal surfaces of TPC material, such as electrodes, and impurities in LXe are believed to be the main background source at the single/few electrons level. To improve our understanding and in an attempt to suppress the single/few electrons background, a sealed TPC with a cylindrical
acrylic field cage and fused silica windows is developed. In an attempt to further suppress the electrode-induced single electrons, a graphene-coated electrode is used.

In this paper, the design and operation of the sealed TPC are described in Sec. 2, including a COMSOL simulation for the design optimization. We investigate the purification efficiency and out-gassing rate based on the LXe purity evolution and a simple purification model, in Sec. 3, followed by a discussion on the rates and production mechanisms of single electrons and their correlation with the LXe purity and electrode materials.

2 Detector design and operation

2.1 Design of the sealed TPC

The schematic design of the sealed TPC is shown in figure 1 (left). A 3D mechanical design is shown on the right which reflects the actual size and structural details of each component. A target volume of \( \Phi 63 \text{ mm} \times h 59 \text{ mm} \), corresponding to 0.54-kg of LXe, is defined by an acrylic cylinder (orange color). A grounding top screening (TS) electrode is installed to protect the PMTs from the high voltage (HV) on anode electrode. Etched stainless steel (S.S) mesh, as shown in figure 2 (left), is used as TS, anode and gate electrode (3) respectively. The mesh pitch is 2 mm and the wire diameter is 0.1 mm, resulting in an optical transparency of 92%. Two pieces of fused silica windows (2 and 9) are placed at the top and bottom of the acrylic cylinder for isolating the LXe target volume from outside. Teflon o-rings are placed between the acrylic flange and fused silica windows for sealing. For the bottom fused silica window, a single-layer graphene was coated on the surface to serve as the cathode electrode (8) with \( \sim 96\% \) transparency [11]. The coating was done by Graphene Laboratories Inc. [12]. To make a better HV connection, gold powder was coated on the edge of the fused silica window as shown in figure 2 (right). Four field-shaping rings (5) are connected via a resistor chain to ensure a uniform drift field between the negatively biased cathode and the gate at ground potential. The distance between the bottom shaping ring and cathode is doubled due to insufficient installation space caused by protrude structure (10) for holding the bottom silica window, thus a resistor with twice resistance value is used for this region. A thin layer of PTFE (6) is placed on the inner wall of the TPC to increase the light collection. Four 1” PMTs (Hamamatsu R8520, 1) are placed above the top fused silica window for signal detection.

The liquid surface is precisely kept in the middle of anode and gate electrodes at 2.5 mm above gate, controlled by a open slit (4). During detector operation, the purified xenon is continuously filling into the inner TPC through an acrylic tube (7). Once the liquid surface reach the position of the slit, the overflowed LXe falls into S.S vessel where the TPC sited, and then being pumped out for purification. The purified xenon, through a SAEN getter, is re-liquefied and fed into the TPC. Although the TPC is not fully sealed due to the small slit at the liquid overflow position, the purified xenon is always fed directly into the LXe target without mixing to the xenon outside of the TPC, thus improving the purification efficiency. The gas gap is automatically obtained at the position of the liquid xenon overflow without the need of extra liquid level control.
Figure 1. (Left) The conceptual design of the sealed TPC. (Right) The 3D TPC design: 1 - Four 1" PMTs on top array. 2 - Fused silica window. 3 - TS, anode and gate electrodes. 4 - Slit for liquid level control. 5 - Field-shaping rings in copper. 6 - PTFE sheet for increasing light collection. 7 - Acrylic tube for liquid xenon filling. 8 & 9 - Graphene cathode: graphene-coated on fused silica window. 10 - “Protrude” structure for holding the fused silica window.

Figure 2. (Left) Etched S.S mesh as TS, anode and gate electrodes. (Right) Graphene-coated fused silica window as cathode with gold-coated on the edge for HV connection.

An electric field simulation was performed to investigate the TPC field uniformity using a finite element analysis software package COMSOL [10]. 3D model was built for precise estimation of field distribution. Limited to computing power, the etched mesh were modeled approximately as parallel wires with diameter of 0.1 mm while the graphened-coated cathode was modeled as a plate.
The field distribution from simulation is shown in figure 3. The anode and cathode are set at 4.0 kV and -1.5 kV respectively, which is the HV setting for all the presented data in the paper. The target volume of TPC was divided into two parts, center \((r < R/2)\) and edge \((r > R/2)\) according to the events distribution as shown in figure 5 (left). \(R\) is radius of the target volume. Most of events are localized in the edge region of the TPC due to the high self-shielding power of LXe, so the field distribution in this region was investigated more closely. The drift and extraction field as a function of \(z\) in edge region is shown in left and right of figure 4, respectively. The black solid line is the mean field in each \(z\) bin. The dashed-vertical lines in figure 4 (left) represent the positions of the electrodes, shaping rings (SRs) and the protrude structure. The high field near the gate is caused by the field leaking from the high field region between gate and anode, while the high field around protrude is due to the dielectric constant difference between LXe and acrylic. To avoid the effect of field non-uniformity, the region from the middle of SR1 and SR2 to SR4 is used for the events selection in our main analysis, which gives a drift field of \((255 \pm 8)\) V/cm as shown in figure 4 (left). In right of figure 4, the positions of the electrodes and liquid surface are marked as dashed-vertical lines, \((5.3 \pm 0.8)\) kV/cm extraction field in LXe can be achieved with current HV setting.

**Figure 3.** The simulated electric field in TPC by COMSOL with anode and cathode at 4 kV and -1.5 kV, respectively.

**Figure 4.** Drift (left) and extraction field (right) as a function of \(z\) in the edge region of figure 3.
2.2 Detector operation

For stable operation of the TPC in a high purity LXe environment, a cryogenic system and a purification system have been built. The cryogenic system consists of a pulse tube refrigerator (PTR) from Iwatani corporation, a heat exchanger and a vacuum insulated S.S vessel. The PTR consists of a PDC08 cold head and an SA115 helium compressor, providing 40 W of cooling power at 165 K. During operation liquefied xenon drips through a 1/4” S.S tube into the vessel where the TPC is located. Benefit from the sealed structure, only a small amount of xenon is required to keep a stable operation. In total 1.13 kg xenon is used with 0.54 kg sensitive target inside the sealed TPC. The vessel is connected to a gas purification system, which contains a SAES Getter (model PS3-MT3-R-2) for removing impurities such as water and oxygen from xenon gas down to part-per-billion (ppb) level. The detailed configuration of the cryogenic and purification system can be found in [13].

To investigate the detector performance, a 122 keV $^{57}$Co gamma ray source was placed externally for detector calibration and electron lifetime monitoring. The source was placed outside the detector at the same height as the TPC center during calibration. Without LXe surrounding the sealed TPC, the low energy gamma rays can easily reach the sensitive LXe target volume thus produce sufficient interaction rate for detector performance study. To record the signals, the PMT waveforms are digitized by CAEN V1720 FADC with a sampling frequency of 250 MS/s after a low noise amplifier ($\times 10$). The digital signals are read out by a PC via a CAEN A2818 optical controller and recorded for further offline analysis.

3 Results and discussion

3.1 Calibration with $^{57}$Co

Two-phase xenon TPC allows the reconstruction of 3-dimensional (3D) positions based on the detection of S1 and S2 signals. A simple $(x, y)$ position reconstruction based on center-of-gravity method is used. Figure 5 (left) shows the reconstructed position of the events from $^{57}$Co source which is placed on the right-bottom in $(x, y)$ coordination. Most of events are localized on the edge of the TPC, due to the strong self-shielding property of LXe. The reconstruction capability is quite degraded for edge events due to its insensitive to S2 pattern. The $z$ position can be inferred from the drift time of ionized electrons, i.e. the time difference between S1 and S2. In figure 5 (right), the location of gate and cathode electrodes, denoted as red dashed lines, can be clearly observed in the drift time distribution. The locations of the four field-shaping rings also can be identified (magenta dashed lines) which shows the impact of non-uniform shaping rings in the design. The valley is probably caused by the electrons attachment on the TPC wall around shaping rings locations. The descending step around $\sim35 \mu$s is caused by a protrude structure as shown in figure 1 (right) for holding the bottom silica window.
Figure 5. (Left) Reconstructed ($x$, $y$) position based on a simple center-of-gravity method for $^{57}$Co gamma rays interacting in the TPC. The red dashed circles denote the radius $R$ and $R/2$ of the LXe target volume respectively. (Right) The drift time distribution. The red dashed lines indicate the location of gate and cathode electrodes respectively. The magenta dashed lines show the location of field-shaping rings while the green dashed line is the location of the protrude structure.

Figure 6. (Left) Correlation of the observed S1 and S2 signals in number of photo-electrons (PE) from $^{57}$Co gamma rays interacting in the liquid xenon target. (Right) S2 as a function of drift time from these events. An exponential fit was applied to the mean S2 values (magenta dots) from each drift time bin in the range of [10, 26] µs to obtain the electron lifetime (see text). The drift time window is selected to avoid the non-uniform drift field outside the range shown in figure 4.

A representative dataset is shown in figure 6. Left plot shows the Log$_{10}$(S2) - S1 space from $^{57}$Co. The location of the 122 keV peak gives a mean S1 of 16.3 PE and S2 of 11,922 PE. The photon detection efficiency ($g_1$) and the electron detection factor ($g_2$) are obtained by comparing the observed S1 and S2 values with the yield of 122 keV monoenergetic peak in the Noble Element Simulation Technique (NEST) calculator [14]. Based on NEST calculator, 5685 photons and 3344 electrons are expected from 122 keV gamma line at 255 V/cm drift field, giving $g_1 = 0.003$ PE/$\gamma$ and $g_2 = 3.6$ PE/e$^-$ in this detector setup. It is expected that this detector geometry would result in a much lower light collection efficiency, compared to the dark matter detectors such as XENON1T [15] and LUX [16], due to the lack of a bottom PMT array and additional light transmission loss through the fused silica window. Nevertheless, the resulting $g_2$ is sufficiently large, allowing us to observe
single electrons drifting in the detector and to further study the single electron rate and its correlation with detector parameters.

The S2 dependence on drift time ($t_d$) is shown in the right plot, where an exponential fit of $S2(t_d) = S2(0) \exp(-t_d/\tau)$ was applied to derive the electron lifetime ($\tau$). The magenta dots are the gaussian mean of S2 in each $t_d$ bin. The middle part of TPC in $t_d$ range of [10, 26] $\mu$s, corresponds to the (255 ± 8) V/cm field region in figure 4 (left), was selected for the fitting, and resulting in a measured electron lifetime ($\tau$) of (456 ± 96) $\mu$s as indicated by the red dashed line. The S2 was slightly dropped with the drift time approaching to gate and near the bottom caused by the field deformation mentioned in Sec. 2.1. The data with drift time below 10 $\mu$s and above 26 $\mu$s was not included in the electron lifetime fitting.

### 3.2 Time evolution of purification

To investigate the purification efficiency of the sealed TPC, we monitor the electron lifetime at different gas xenon circulation and purification speed. The getter used (SAES model PS3-MT3-R-2) has a maximum purification speed of 5 standard-liter-per-minute (SLPM) for nitrogen, helium and argon, but 3 SLPM for xenon according to the specification. During the detector operation, the xenon flow rate through getter was set at different values to investigate the purification efficiency and understand the xenon purity. The time evolution of electron lifetime $\tau$ was monitored for several days using the calibration data and divided into four periods as shown in figure 7.

![Figure 7](image)

**Figure 7.** Electron lifetime as a function of time for different purification settings. A simple purification model (blue lines, see text) is used to fit the data to obtain parameters relevant to the out-gassing and liquid purity. The highest electron lifetime obtained is a little over 0.5 ms, with large uncertainties due to the limited drift time window. Data were taken in 2019.

A simple purification model was developed to describe the electron lifetime evolution during our run. During the gas xenon circulation and purification, the impurity concentration in the target LXe can be described as,

$$\frac{M}{\rho} \frac{dn(t)}{dt} = R_o - n(t) \eta F$$  \hspace{2cm} (3.1)
where \( n(t) \) is the oxygen-equivalent electro-negative impurity concentration in unit of part-per-billion (ppb) in xenon. \( M \) is the total mass of LXe inside the TPC (~0.54 kg in this design). \( \rho \) is the density of xenon gas (5.9 \times 10^{-3} \text{ kg/liter}). \( R_o \) is a constant “effective” out-gassing rate from detector materials into the LXe target. Note that the out-gassing here is not the same concept in vacuum, but including the impurities that are diffused/dissolved/leaked into the LXe target. \( F \) is the xenon gas circulation flow rate. We added the \( \eta \) term to describe the purification efficiency. In case the impurity in the xenon is not fully removed by the getter, or if additional impurities are added to the purified xenon gas before it reaches the target volume inside the TPC, the \( \eta \) term will be less than 1.

The time evolution of the electron lifetime, at a constant purification speed \( F \), thus can be obtained as,

\[
\tau(t) = \frac{368}{n_0 e^{-\frac{\rho n_0 F}{M} t} + \frac{R_o}{\eta F} \left( 1 - e^{-\frac{\rho n_0 F}{M} t} \right)} \] [\mu s] \quad (3.2)
\]

\( n_0 \) is the initial (\( t = 0 \)) concentration. The constant 368 is the electric field dependent term which can be derived from Ref.[17] to relate the electron lifetime and impurity concentration in LXe as, \( \tau(t) \approx \frac{368}{n(t)} \) [\mu s]. The electron lifetime would reach a plateau after reaching an equilibrium,

\[
\tau(t \to \infty) = \frac{368 \times \eta F}{R_o} \] [\mu s] \quad (3.3)

Each of the four periods in figure 7 is fit with the relevant purification model equations. The fitting results are summarized in Tab. 1. The period of P-1 is fit with Eq. 3.2 with \( F = 2 \) SLPM while the P-2 is fit with a constant value of Eq. 3.3 suppose the maximum electron lifetime has been reached after the flow rate being switched to \( F = 5 \) SLPM. The model fitting gives 0.51 \pm 0.02 and 0.25 \pm 0.01 of \( \eta \) for P-1 and P-2 respectively. Less than 100% purification efficiency is obtained in P-1 due to the LXe outside the TPC which is largely contaminated with higher out-gassing volume compared to the inside of the sealed TPC. The further drop of purification efficiency from P-1 to P-2 indicates the degrade of the getter’s purification capability after reaching its maximum specified flow rate (3 SLPM) for xenon. The effective impurity out-gassing rate \( R_o \) of \((4.0 \pm 0.3) \times 10^{-11} \) liters/s is obtained from the fit.

The period of P-4 is fit with Eq. 3.2. A \( \eta \) of \((0.21 \pm 0.02)\) is achieved which is consistent with P-2 at the same flow rate of 5 SLPM. Note that the large fluctuation of \( \tau \) in June is mostly caused by the operations on circulation pipes for the purification system upgrade. A higher electron lifetime was achieved in June compared to May, which indicates that the out-gassing outside the TPC is smaller in June compared to May after ~1 month of purification, which resulted in a lower effective impurity out-gassing rate \( R_o \) of \((2.0 \pm 0.3) \times 10^{-11} \) liters/s.

During the period of P-3, the getter was bypassed for understanding the purification process but the flow was kept at 5 SLPM in the bypass pipes, thus the impurity concentration in LXe can be described by Eq. 3.4 and solution in 3.5.

\[
\frac{M}{\rho} \frac{dn(t)}{dt} = R_o + n_{out} F \] (3.4)
Table 1. The fitting results from figure 7. Note that the $R_o$ from P-1 fitting is used in Eq. 3.3 for P-2 fitting.

| Periods | Circulation              | $n_0$ [ppb] | $R_o$ [$10^{-11}$ liter/s] | $\eta$ | $n_{out}$ [ppb] |
|---------|--------------------------|-------------|------------------------------|--------|-----------------|
| P-1     | 2 SLPM through getter    | 66.2 ± 7.0  | 4.0 ± 0.3                    | 0.51 ± 0.02 | n/a             |
| P-2     | 5 SLPM through getter    | n/a         | n/a                          | 0.25 ± 0.01 | n/a             |
| P-3     | 5 SLPM bypass getter     | 0.79 ± 0.08 | negligible                   | n/a    | 32.4 ± 2.4      |
| P-4     | 5 SLPM through getter    | 22.5 ± 3.0  | 2.0 ± 0.3                    | 0.21 ± 0.02 | n/a             |

\[
\tau(t) = \frac{368}{n_0 + (R_o + n_{out} F) \rho_M t} \quad [\mu s]
\] (3.5)

where $n_{out}$ is the impurity concentration in the LXe outside the sealed TPC where the xenon is taken out through the circulation. In this diagnostic run, impurity from outside of the sealed TPC is brought inside quickly reducing the liquid xenon purity thus lowering the electron lifetime.

By fitting the period of P-3 with Eq. 3.5, $(2.7 \pm 0.2) \times 10^{-9}$ liter/s of $(R_o + n_{out} F)$ was obtained. The $R_o$ is very small according to the values obtained from P-1 and P-4 periods. An impurity concentration of $(32.4 \pm 2.4)$ ppb is obtained in the liquid xenon outside the sealed TPC, considering the 5 SLPM flow rate $F$ and negligible $R_o$. This indicates the LXe outside the sealed TPC contains much higher impurity than that inside. In the current design of the sealed TPC, the LXe in the sensitive target is always first mixed with the LXe outside, then passing through the getter, effectively increasing the burden of the getter to purify the LXe outside the target and reducing the purification efficiency. In addition, the impurity gas molecules from the outside the sealed TPC can “leak” into the LXe target through the small slit between the anode and gate. That “leak” certainly increases the value of $R_o$. A LXe detector with the target volume completely sealed will not only have reduced $R_o$ but also improved purification efficiency, thus electron lifetime can be further improved. A completely sealed TPC would require a different cryogenic and purification system design and will be pursued in the future.

3.3 Single electron detection

Understanding and controlling the background at single and a few electrons level is critical to the sensitivity of sub-GeV dark matter electron scattering or CEνNS of low energy reactor neutrinos. There are two types of single/few electrons background. One is the prompt single electron background within one max drift time window, typically at tens or hundreds $\mu$s following a large signal (S1 or S2). The other type is the delayed single electrons that can extend to hundreds of ms following a large signal (S1 or S2). In this study, we investigate the prompt single electron rate and its correlation with impurity levels in LXe or different electrodes. The study of delayed single electron emission [18] requires much lower background and will be pursued in the future.

3.3.1 Single electron identification

The raw data for single electron study was acquired with window length of 80 $\mu$s with 50% post trigger. Most of the events were triggered on S2 peak, thus ~40 $\mu$s time window after S2 can be used for extracting the single electrons from the photoionization by S2 light. Figure 8 shows the
delay time of the small S2s after the main one. Three clear peaks can be observed, indicating the location of the gate, protrude and cathode respectively. The peaks (red dashed lines) around gate and cathode electrodes are considered to be from the photoionization of electrode surface by the main S2. The peak (green dashed line) around the protrude structure is most probably caused by the electrons accumulation on the edge of the acrylic material. The other region is the photoionization of main S2 light on the impurities in the bulk LXe, and overlapped with the PMT after-pulses.

**Figure 8.** Delay time of the small S2s, corresponding to single or a few electrons, after the main S2 from a recoil event. The red dashed lines indicate the location of the gate and cathode electrodes respectively, while the green dashed line is the location of the protrude structure for holding the fused silica window as shown in figure 1 (right).

**Figure 9.** Typical small S2s spectrum within 2 µs time window for gate (left) and cathode (right) electrode respectively. The spectrum was fit with a sum of 4 Gaussians, supposing that the spectrum comprises a sum of one to four electrons, multiplied by a function (see text) to take into account the detection efficiency.

To extract the single electron signals, the events within 2 µs time window around the peak of the gate (or cathode), as shown in the pink shaded region in figure 8, were selected. The corresponding S2 spectra are shown in figure 9. The spectra are fit using a sum of several Gaussian functions with mean $i \mu$ and standard deviation $\sqrt{i \sigma}$, where $i$ represents 1~4 electrons, multiplied by an efficiency curve, described by an empirical function $f(S2) = \frac{1}{e^{(S2-A)/B}+1}$ with $A$ and $B$ as free parameters. This fit assumes that the S2 spectrum comprises a sum of one to a few electrons S2 signals with.
the first Gaussian ($\mu, \sigma$) provides the detected PEs per electron which has been extracted to GXe. The efficiency curve reflects the efficiency of the S2 peak-finder algorithm. The single electron gain ($\mu \pm \sigma$) of $4.7 \pm 2.3$ PE/e$^{-}$ and $4.3 \pm 1.8$ PE/e$^{-}$ were derived from the data for gate and cathode electrodes respectively, which is consistent with each other. In addition, the single electron gain can also be estimated based on the $g2$ and electrons extraction efficiency at gas-liquid interface. The extraction field is 5.3 kV/cm in LXe from Comsol simulation corresponds to a extraction efficiency of $\sim 90\%$ [19]. The single electron gain will be 4.0 PE/e$^{-}$ considering $g2 = 3.6$ PE/e$^{-}$ from Sec. 3.1, which is consistent with the fitting results.

### 3.3.2 Photoionization on electrodes and LXe impurities

The single electron rate in each $\mu s$ delay time after the main S2 is defined as the number of single electrons produced per primary S2 electrons after the electron lifetime correction. The number of primary S2 electrons is the electrons that have been extracted to the gas phase. The single electron rate as a function of its delay time is shown in figure 10 (left) for runs with different electron lifetime (or liquid purity).

To understand the photoionization mechanisms from different materials, the single electron rate from gate, cathode and LXe bulk are investigated separately. For electrons generated on the gate and cathode electrodes, we used the average rate within $2 \mu s$ delay time window around the peak rate. For electrons generated on the impurities in the bulk LXe, we chose the rate within [10, 26] $\mu s$ delay time window in the center of the TPC to avoid the potential field distortion in top and bottom TPC region. The corresponding delay time regions are the shaded-bands in figure 10 (left). The rates from each components are shown in figure 10 (right). The single electron rate from LXe bulk decreases with the increasing of electron lifetime due to the purity improvement, while the rate from the gate and cathode are less affected by the LXe impurities as expected.

**Figure 10.** (Left) The single electron rate as a function of the delay time at different electron lifetime. see more explain in text. (Right) The single electron rate from gate, cathode and LXe bulk region, as a function of its electron lifetime. The rate is the average value from the corresponding shaded-band in the left plot.

Although the single electron rate has been corrected with electron lifetime, it still decreases with the delay time. This can be explained by the smaller number of S2 photons hitting the lower part of the TPC. A simple Solid Angle (SA) model can be used to model the photon emission from the location where S2 is produced. The S2 photons are mostly produced around anode wires due
to the strong local electric field, and emitted isotropically. In the SA model, we assume the S2 is produced in the center of the anode electrode, thus the solid angle inside TPC gradually decreases with increasing of TPC depth. One example single electron rate as a function of its delay time is shown in figure 11 (left). The rate between the delay time of [10, 26] µs was fit with the SA model. The fitting is slightly deviated from the data caused by the photon reflection on the thin PTFE sheet on TPC wall. This distribution indicates that the single electrons from the LXe bulk are most likely associated with the neutral impurities [18] which are more evenly distributed in LXe than negative ions caused by electrons attached to the impurities. The larger deviation from the SA model for events near the gate electrode is most likely caused by the negative ions accumulation at the upper region of the TPC, with a higher photoionization probability than the neutral impurities. Another possible reason is the inaccurate drift time correction due to the field distortion as described in Sec. 3.1.

![Figure 11](image)

Figure 11. (Left) The single electron rate as a function of its delay time for data with 91.1 µs electron lifetime, fit with the solid angle model in range of [10, 26] µs delay time. The inset is a zooming of the fit region. (Right) Photoionization rate as a function of the impurities in the LXe bulk. The impurity in ppb is calculated from the electron lifetime (see text for details). The data-points is fit with a linear function.

The photoionization probability can be estimated for different electrode materials and different LXe impurities level as following. The photons that produced by one extracted electron in GXe is calculated by the empirical equation: $N_\gamma = \alpha (\varepsilon_e / p - \beta)p_x$. $\alpha$ is the amplification factor and $\beta$ is the threshold of reduced field for proportional light production. $\alpha = 120$, and $\beta = 1.3$ kV/cm/atm [20] are used in our calculation. The electric field $\varepsilon_e$ of 9.6 kV/cm in S2 production region is from the COMSOL simulation. In our measurement, the gas pressure ($p$) is controlled and kept at 2.2 atm. The gap ($x$) for proportional light production is 0.25 cm. In the end, 202 $\gamma/e^-$ of $N_\gamma$ can be derived based on the parameters above.

Considering the solid angle, 92% gate transparency, and 96% transparency of the single-layer graphene cathode [11], the number of photons hitting the electrodes can be estimated. Based on the number of electrons emitted from the electrodes, and photons received accordingly, the photoionization probability of the electrodes can be obtained. The photoionization probability of the stainless steel gate is $7.7 \times 10^{-5} e^-/\gamma$, which is consistent with the value of $\sim 1.0 \times 10^{-4} e^-/\gamma$ in Ref. [21] for stainless steel. The photoionization probability of graphene is estimated to be
$5.0 \times 10^{-5} \text{e}^-/\gamma$, which is slightly lower than the stainless steel. The result is reasonable considering the slightly higher work function of graphene (4.5–4.8 eV [22]) than that of the stainless steel (4.3 eV [23]).

In LXe, the single electron rate can be explained by the photoionization on oxygen-equivalent impurities. The cross section of the xenon scintillation light on oxygen atoms is $\sim 1 \text{Mb}$ with very low efficiency ($<1\%$) [24]. Assume 1 ppb concentration of oxygen in LXe, it will give a photoionization rate of $\sim 1.4 \times 10^{-5} \text{e}^-/\gamma/\text{m}$. In our measurement, the photoionized electrons within [10, 26] $\mu$s delay time from each extracted electron can be calculated by integrating the histogram in figure 10 (left). The number of photons cross this LXe region can be estimated using the solid angle coverage and the gate transparency. Assume a 5 cm mean path length for photons within the [10, 26] $\mu$s delay time window taking into account the reflection on TPC wall, the photoionization rate in LXe was calculated and shown in figure 11 (right) for different electron lifetimes. A linear fit results a value of $4.5 \times 10^{-6} \text{e}^-/\gamma/\text{m}$ for every ppb impurity concentration, which is compatible with the calculation from the photoionization cross section on oxygen. The results is also close to the estimated $(5-20) \times 10^{-5} \text{e}^-/\gamma/\text{m}$ from the LUX experiment [18].

### 4 Conclusion

In this work, we demonstrated a semi-sealed LXeTPC with a graphene-coated fused silica window as the cathode electrode. The effectiveness of the LXe purification is studied using the electron lifetime evolution data with a simple purification model. It shows a much cleaner liquid xenon purity in LXe target inside the sealed chamber, compared to that outside, achieving an electron lifetime of 0.5 ms, with uncertainties limited by the drift length of the TPC. We expect further improvement of purification efficiency with a fully-sealed TPC, which will be developed in the future.

We investigated the single electron rate caused by the photoionization of scintillation photons on electrode materials and impurities in LXe. The graphene shows a little improvement, in terms of photoionization probability, compared to stainless steel. The photoionization rate of impurities in LXe shows that the prompt single electrons are caused mainly by the oxygen impurities in the bulk LXe.

The TPC concept demonstrated here serves as a basis for further development of the sealed TPC technique aiming to significantly improve the purification efficiency of LXe in the target, and to reduce the single/few electrons background for future experiments to search for sub-GeV dark matter via electron scattering [25], reactor neutrino detection via the CEνNS process [26], and the next generation multi-purpose liquid xenon experiment, e.g. DARWIN [27], for dark matter and neutrino physics.

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