AXEL : High pressure Xe gas TPC for neutrinoless double-beta decay search

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Abstract. AXEL is a high pressure xenon gas TPC with a unique cellular readout structure, ELCC (Electroluminescence Light Collection Cell), for neutrinoless double-beta ($0\nu\beta\beta$) decay search. We developed two prototype detector and evaluated them. The small size prototype detector (10-L pressure vessel) is constructed first and evaluated its performance to demonstrate the concept of the ELCC. The large size prototype detector (180-L chamber) are being developed to get the know-how for enlargement and for background study. The estimated energy resolutions at the Q-value of $0\nu\beta\beta$ decay of $^{136}$Xe are 0.82$\sim$1.74% for the former prototype and 0.67% for the latter.

1. Introduction
AXEL is a high pressure xenon gas TPC to search for neutrinoless double-beta ($0\nu\beta\beta$) decay. The concept of the detector is described in [1]. We plan to begin physics run from 2022 with 100-kg scale $^{136}$Xe. As a technical demonstration, we developed two prototype detectors, one is 10-L size prototype to demonstrate of the usefulness of the ELCC, the detection plane of ionization signals, for a high energy resolution TPC and the other is 180-L prototype to establish technology for enlargement.

Event topology is reconstructed from hit pattern and waveform and used to reject backgrounds. To distinguish $0\nu\beta\beta$ signals from gamma-ray background, in particular gamma-rays irradiated from $^{214}$Bi, an algorithm using three dimensional convolutional neural network (3D-CNN), a kind of a deep learning, has been studied. In the deep learning selection, signal acceptance is 53.8% with background rejection rate of 99.2%. We have to make the following correction of our presentation slide in TAUP2019: signal acceptance of 50% and background rejection ability of 99.95% are the performance of pre-cut for the deep learning selection.

2. 10-L Prototype Detector
Figure 1 shows the picture of 10-L size small prototype detector. In this version, the cell configuration of the ELCC is square pattern and 7.5 mm-pitch. The performance of this prototype is evaluated with 8 bar xenon gas and $^{133}$Ba gamma-ray source (356 keV). The distribution of the photon counts (corresponds to energy spectrum) after some cuts and correction is shown in Figure 2. To evaluate the energy resolution, the first five peaks (29.8 keV, 33.0 keV, 48.0 keV, 51.2 keV, 81.0 keV) are fitted with “Gaussians + linear function” and the last four peaks (276.4 keV, 302.0 keV, 326.0 keV, 356.0 keV) with “Gaussian + exponential
function” to account for contributions from the background. The obtained energy resolution is 2.54% (FWHM) at 356 keV and this corresponds to 0.97% (FWHM) at Q-value of 0νββ decay of 136Xe, 2458 keV, converted by the function: \sqrt{E}. With the fitting results of the all peaks, performance of the detector at Q-value, 2458 keV, is estimated with two assumptions: energy resolution \propto A\sqrt{E} and energy resolution \propto A\sqrt{E} + BE^2. With the former assumption, extrapolated value is 0.82% and with the latter, 1.74%.

Figure 1. 10-L prototype detector.

Figure 2. Distribution of photon counts irradiated by gamma-rays from 133Ba.

3. 180-L prototype detector
We also developed the 180-L large prototype detector to acquire the know-how for enlargement and for background study. The structure of the detection plane, ELCC, is changed from one-piece style to unit style. The configuration of the cell is optimized by simulation. The cell pattern is changed to hexagonal pattern for the distance between all neighboring cells to be same. The cell pitch is 10 mm in this prototype detector. Figure 3 is the picture of the ELCC
in the first phase of this prototype. We used one unit to evaluate the detector performance as the commissioning of the first phase prototype detector.

![Figure 3. ELCC of the 180-L prototype in the first phase.](image)

3.1. **Fiducial Cut**

The inner 29 channels are defined as fiducial channels and the outer channels are regarded as veto channels. Events which have hits only in the fiducial channels are selected. Figure 4 shows the configuration of the fiducial and veto channels and the distribution of photon counts before and after the fiducial cut. The peak around 9,000 photons is the peak of characteristic X-ray from xenon, \(\sim 30\) keV.

![Figure 4. Distribution of photon counts around 30 keV before and after fiducial cut.](image)

3.2. **EL gain calibration**

The EL gain of each channel is calibrated cell by cell using 30 keV peak. For each cell, events are selected in which it has the highest number of detected photons and in which no cells other than its next two channels are hit. The gain of each cell is determined using the fitting result of “gaussian fitting” to the peak of characteristic X-ray.
3.3. Correction of MPPC saturation
We use MPPCs (Multi-Pixel Photon Counter, Hamamatsu inc.) as photo sensors of the ELCC. Because of the limitation of the number of pixels, signal saturates when the number of the incident photons is close to the number of pixels, signal saturates. We corrected this effect using the following function (model):

\[ N_{\text{true}} = \frac{N_{\text{observed}}}{1 + \tau/(N_{\text{pixel}} \cdot \Delta t)}, \]

where \( N_{\text{observed}} \) is the number of observed photons, \( N_{\text{pixel}} \) is 3600 in this prototype, \( \Delta t \) is a time window for the correction, and \( \tau \) is so-called “recovery time” of MPPC, which parameterizes the correction. The recovery time of each MPPC was set to be 140 ns for all channels in this analysis.

Figure 5 shows the obtained distribution of photon counts after the cut and corrections described above. Two peaks are clearly seen. The peak with lower photon counts is the characteristic X-ray of K\textsubscript{α} peak (29.78 keV) and the other is the characteristic X-ray of K\textsubscript{β} (33.02 keV). Energy resolution is evaluated by fitting these two peaks by Gaussian. The obtained energy resolution is 6.14% (FWHM) at 29.78 keV and this is comparable to the simulated value, 6.11% (FWHM).

![Figure 5. Distribution of photon counts around 30 keV before and after corrections.](image)

4. Summary
We are developing the high pressure xenon gas TPC with the unique cellular readout structure for 0νββ decay search. Two prototype detectors were developed to evaluate the performance of the AXEL detector. One is the small prototype detector (10-L size) the other is the large prototype (180-L size). With the former prototype, we proved the concept of the readout structure, ELCC. The obtained energy resolution is 2.54% (FWHM) at 356 keV and estimated performance at the Q-value, 2458 keV, is 0.82~1.74% (FWHM). The latter prototype is constructed to get the know-how of enlargement of the detector and to study backgrounds. Now, it is commissioning phase and its performance was evaluated with a small number of channels (56 channels). The obtained energy resolution was 6.14% (FWHM) for the peak of the characteristic X-ray from xenon (29.78 keV) and in good agreement with the simulation result.

References
[1] Ban S, Nakamura D K et al. 2017 Nuclear Inst. and Methods in Physics Research A, 875, 185-192