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Electroluminescence collection cell as a readout for a high energy resolution Xenon gas TPC

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A B S T R A C T

AXEL is a high pressure xenon gas TPC detector being developed for neutrinoless double-beta decay search. We use the proportional scintillation mode with a new electroluminescence light detection system to achieve high energy resolution in a large detector. The detector also has tracking capabilities, which enable significant background rejection. To demonstrate our detection technique, we constructed a 10 L prototype detector filled with up to 10 bar xenon gas. The FWHM energy resolution obtained by the prototype detector with 4 bar Xenon gas is 4.0±0.30 % at 122 keV, which corresponds to 0.9∼2.0% when extrapolated to the Q value of the $0\nu\beta\beta$ decay of ^{136}Xe.

1. Introduction

Observation of neutrinoless double beta decay ($0\nu\beta\beta$) is important to reveal the nature of the neutrino, such as the neutrino mass hierarchy, its absolute mass and whether or not it is a Majorana particle [1]. Among potential double beta decay nuclei, ^{136}Xe offers several advantages in terms of detecting this process. The natural abundance of ^{136}Xe is as high as 8.9% and can be enriched using established methods. Very high energy resolution is possible in gaseous xenon, in principle, due to its large ionization yield and small fano-factor. It also emits scintillation light. The EXO experiment uses xenon and obtained 1.1×10^{25} yrs as the 90% C.L. lower limit of the $0\nu\beta\beta$ half life [2]. The KamLAND-Zen experiment obtained 1.07×10^{26} yrs as the 90% C.L. lower limit using xenon dissolved in liquid scintillator [3]. Longer half-life corresponds to lighter neutrino mass, and to further explore smaller neutrino mass up to so-called inverted mass ordering, sensitivity has to reach 6×10^{27} yrs and energy resolution improvement is essential for discriminating radioactive and $2\nu\beta\beta$ backgrounds. A $0\nu\beta\beta$ search using high pressure gaseous xenon was proposed [4] in order to obtain high energy resolution and topological information and experiments have started (NEXT [5]) or planned (PandaX-III [6]). The former experiment utilizes the electroluminescence and the latter the micro pattern gas detector to amplify the ionization electron signal. In these projects, high energy resolutions, 1.82% (FWHM) at 511 keV [7] and 9.6% (FWHM) at 22.1 keV [8], have been demonstrated. Our detector, a high pressure xenon gas TPC, AXEL, adopts a new method to measure ionization electrons by electroluminescence with a cellular structure, which enables high energy resolution for large target mass while maintaining strong background rejection power.

The schematic view of the AXEL detector is shown in Fig. 1. It is a high pressure xenon gas TPC filled with 10 bar ^{136}Xe enriched gas. Ionized electrons are detected by a pixelized readout plane named ELCC (ElectroLuminescence Collection Cell, described in Section 2) placed at electron drifting side. Scintillation light is detected by PMTs on the opposite side of the vessel to obtain the hit timing which is necessary for event fiducialization. In the past, 0.3% (FWHM) energy resolution for the 662 keV gamma ray was demonstrated [9] for ionization chamber filled with xenon gas. We aim for 0.5% as a realistic energy resolution with large volume by adopting the ELCC readout. In this paper, we describe the concept of the ELCC and report its first performance result.

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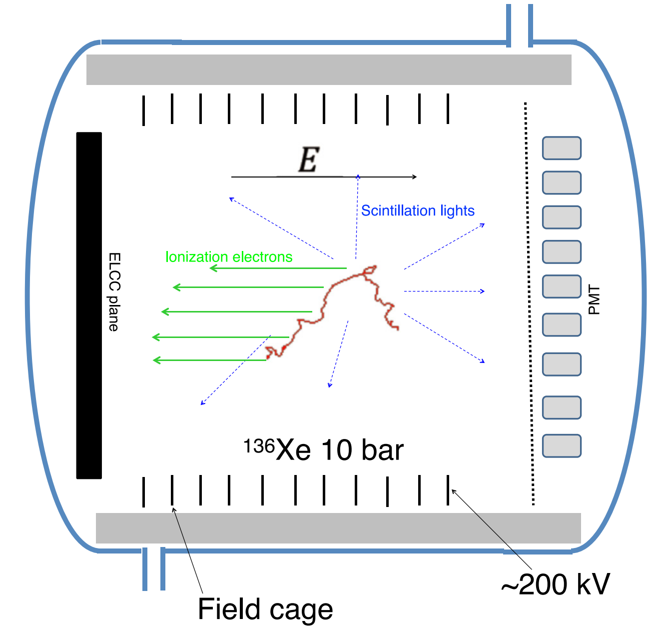

Fig. 1. Schematic drawing of AXEL detector.

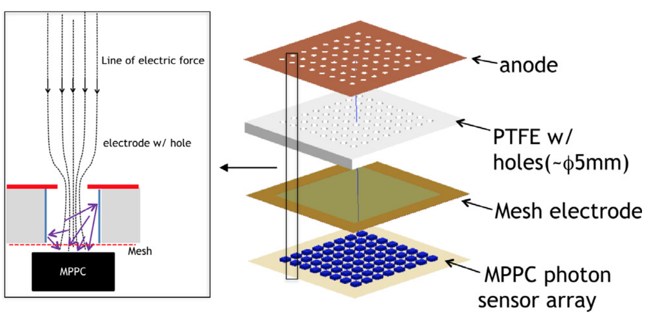

Fig. 2. Structure of ELCC.

2. Electroluminescence light collection cell (ELCC)

2.1. Concept

Electroluminescence (EL) is a process in which electrons accelerated in a high electric field excite xenon atoms and generate de-excitation photons. The EL photons are always generated by the initial electron unlike the avalanche amplification where initial fluctuation is amplified, too. A normal way to utilize the EL process for the radiation detection is applying high voltage between two conductive parallel meshes to generate EL photons. Those photons are detected by photon sensors such as PMT. Such systems exhibit good energy resolution in compact detectors [10]. However, when the detector volume is large, it is difficult to get uniform coverage by photon sensors and the energy resolution is worsened because the acceptance to detected photon depends on the position of radiation inside the detector volume. To solve this problem, we propose the ELCC.

ELCC is designed to measure both energy deposition and event topology. Fig. 2 depicts the structure of ELCC. The EL region is made of a Cu plate, PTFE plate and mesh. The PTFE plate and Cu plate has holes to form cells. For each cell, a SiPM photo-sensor is attached at the back of the mesh electrode to detect EL photons. The mesh is electrically connected to ground and negative voltage (~ -15 kV) is applied to the Cu plate. The space above the ELCC is the target volume, whose drift

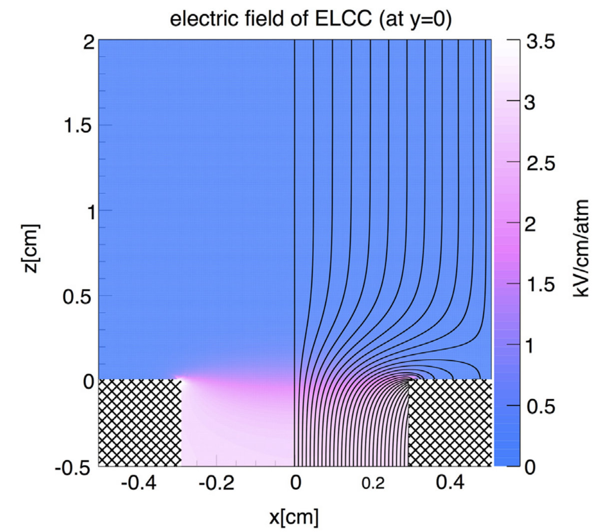

Fig. 3. Calculated electric field at $y = 0$ plane when voltage is applied at 100 V/cm/atm in the drift region and 3 kV/cm/atm in the EL region. Since the basic performance of the gas detector depends on the electric field normalized by pressure, the electric field strength as a color bar is expressed in units of V/cm/atm. The horizontal and vertical axis correspond to x and z axis of the ELCC. Colored contours show the reduced electric field strength. The hatched regions correspond to the PTFE insulator with a $r = 3$ mm hole. Electric field lines have additionally been drawn on the right half of the figure.

field uses the Cu plate of the ELCC as its anode. By applying sufficiently high voltage between the anode electrode and mesh, ionized electrons are collected into cells along the lines of electric field, and generate EL photons, which are detected by SiPMs in each cell. Because the acceptance of the SiPM for the EL light does not depend on the event position in the TPC, ELCC measure number of ionized electrons without any event-position correction. Also, since ELCC is pixelized, it would enable strong background rejection by the event topology. Furthermore, the detection surface can easily be extended to larger areas due to the solid structure of the ELCC. In this paper, z axis is the direction of electron drift, and the x and y axes are parallel to the ELCC plane. In this section, the origin of coordinates is intersection of the central axis of the cell in x–y plane and anode-Cu plane in z axis.

2.2. Optimization

To determine the optimum voltage and geometrical parameters, we simulated the electric field with the finite element method (Gmsh [11] and Elmer [12]). The baseline geometry has a 10 mm cell pitch with a 5 mm deep EL region and a 6 mm diameter hole. The cell pitch will be optimized from the track reconstruction ability and total cost of SiPMs and readout electronics. Since ionization electrons diffuse about 10 mm for 1 m of drift in xenon gas, a 10 mm cell pitch is sufficiently fine, and anything smaller than that is not necessary. In order to maintain the mechanical strength of PTFE insulator, at least 5 mm is required for the EL region. It will be confirmed in Section 2.3 that it is possible to obtain the sufficient number of EL photons for this length.

Fig. 3 shows an example of the calculated electric field distribution. All electric field lines converge on the ELCC hole. Fig. 4 shows the electric field dependence of the collection efficiency of electric field lines defined as the percentage of electric field lines generated above 2 cm of ELCC going into the hole. The efficiency is better for the stronger EL field and weaker drift field. To suppress recombination and to get good energy resolution, the drift field higher than 100 V/cm/atm is desired. Thus, in order to maintain 100% collection efficiency an EL field of $2.5 \sim 3$ kV/cm/atm is required. Fig. 5 shows the dependence of the collection efficiency on cell geometry. The efficiency depends on the aperture ratio of the ELCC hole defined as $(\pi r_{\rm hole}^2)/l_{\rm pitch}^2$, where $l_{\rm pitch}$ is