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AXEL Experiment: Research and Development of a Novel Xenon Gas Scintillation Detector

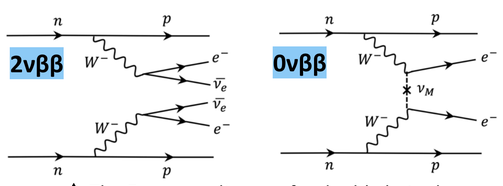
Soki Urano*, A.K.Ichikawa, T.Nakaya, K.D.Nakamura, Y.Iwashita, M.Hirose, S.Akiyama, J.Hikida, S.Hatsumi, L.Evan, Y.Watanabe, and AXEL collabration

*Tohoku University

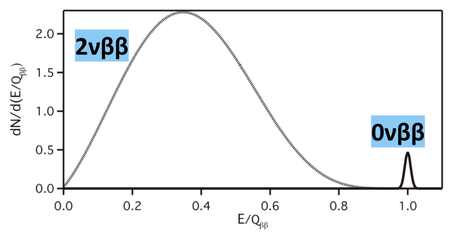
AXEL Experiment

Neutrinoless double beta decay (0νββ)

- If neutrinos are **Majorana particles**, i.e. they are their own antiparticles, then 0νββ can occur.
- Important to understand the origin of
  - Unnaturally light neutrino mass
  - Matter-antimatter asymmetry of the universe
- Very rare
  $T_{1/2}^{0\nu} > 3.8 \times 10^{26}\ yr\ (90\%\ C.L.)$@^{136}Xe[1]
  ⇒ The three requirements for the search
  - **Large mass**
  - **Low background**
  - **High energy resolution**



▲ The Feynman diagram for double beta decay

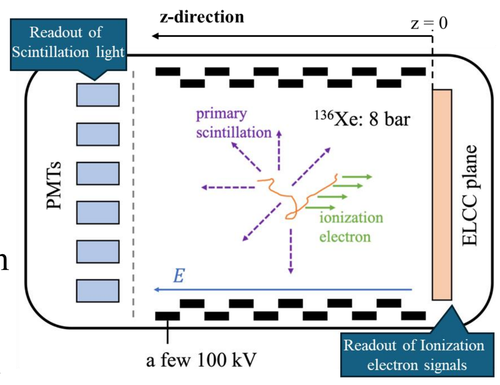


▲ The ideal energy spectrum

AXEL experiment

A Xenon ElectroLuminescence

- High-pressure ^{136}Xe gas TPC for 0νββ search
  - ^{136}Xe is a double beta decay nucleus & an excellent detection medium
- ELCC (ElectroLunescence light Collection Cell)
  - AXEL's unique ionization electron readout system
  - **High energy resolution**
  - Tracking ability ⇒ **Background discrimination**
- **Prototype Energy resolution : 0.67% @ 2615 keV**
  - **z mis-reconstruction contributes 0.24 %**
    ⇒ The low detection efficiency of scintillation light is an issue



▲ AXEL detector schematic

R&D of a Novel Scintillation Detector by Wave-Length Shifting plate (WLS plate)

Scintillation detection for previous measurement

- VUV-PMT × 7 @ 180L prototype
  - Sensitive to the scintillation wavelength of xenon gas (175 nm)
  - **The photosensitive area is 4.2 cm²/unit**
    ⇒ Expansion of the area is difficult due to the high-pressure environment
  - **The expected number of total detected photons is 6.8 @ ^{136}Xe's 0νββ**
    - Cannot distinguish between the "correct" scintillation light corresponding to the EL light and accidental scintillation light within drift (≳ 100 μs) time

    ⇒ z mis-reconstruction

Concept & Structure of the WLS

【Concept】

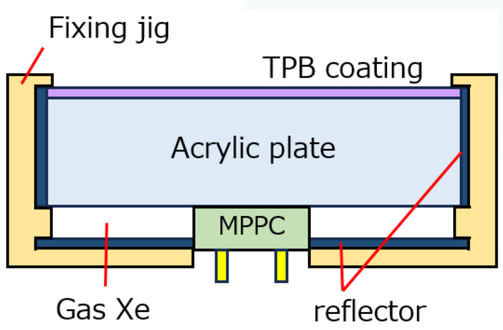
- Achieves both a large photosensitive area and high detection efficiency
  - A combination of photon wavelength conversion and trapping

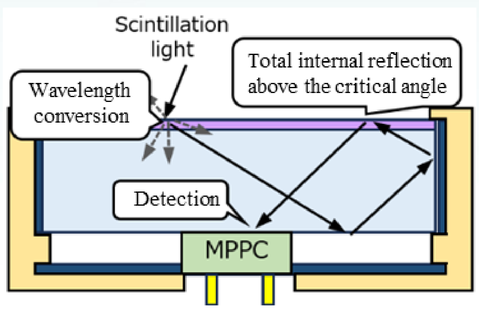
0νββ Scintillation Detection
- If the **average p.e ~ 5/plate**, the detection probability is >99%
- If the **total p.e. ~ 25**, events up to 2 MeV can be distinguished

⇒ **Target value**

【Structure】

- A multi-layer structure consisting of a wavelength-shifter (TPB) coating layer, an acrylic layer, a xenon gas layer, and a reflective film + MPPC (SiPM)
  - TPB converts scintillation light into visible light (175 nm → 430 nm)
  - Trapping photons by reflection





Expected performance

- The photosensitive area is 25 cm²/unit
  ⇒ 6 times that of a VUV-PMT
- Removal of the PMT protection mesh electrode
  ⇒ The number of incident photons is 1.5 times greater
- The estimated detection efficiency for incident VUV-photon is **18%**

7.3 photons/plate is expected

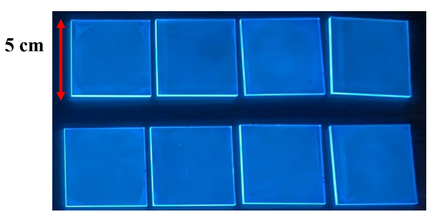
To achieve the target value !


▲Optical simulation of the WLS

Production of the WLS

【Spin coating】

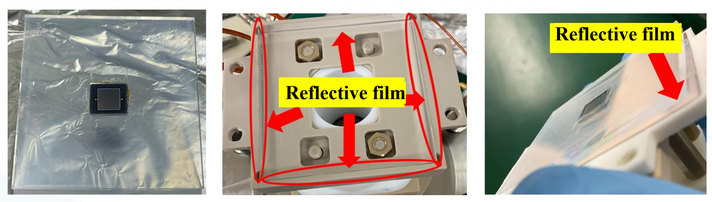
- The performance of the WLS depends critically on whether the TPB coating is uniform and smooth
- Spin coating is a method of coating a substrate by dropping a solution onto it and spinning it at high speed
- To prevent TPB degradation, form a TPB-doped polystyrene (PS) film
  ⇒ TPB/PS mass ratio : 0.8[2]
- **Production of high-quality TPB-coated plates has been successfully established**



▲ TPB-coated acrylic plate irradiated with UV light

【Production】

- TPB-coated Acrylic plate & MPPC (S13360-6075CS) & Reflective film (DF2000MA) & Optical cement (EJ-500)
  - Bonding the TPB-coated plate and the MPPC with optical cement
  - The bottom and sides are covered with the reflective film

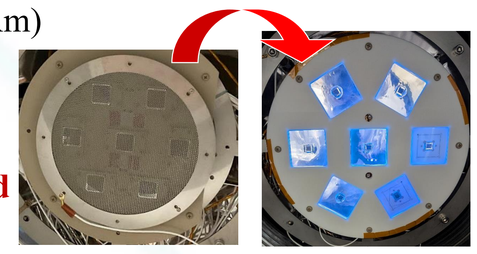


Performance evaluation of the WLS

Evaluation of the WLS in xenon gas

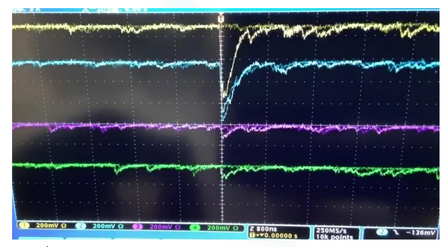
【Test chamber】

- Detect scintillation photons from an α-source (^{241}Am)
  - Placing a VUV-PMT in a symmetrical position to compare the number of detected photons
- **Detected 1.5 times larger than expectation**
  ⇒ Indicate that more than 1 photon is generated per 1 UV photon


▲ WLS implementation on the 180L prototype

【180L prototype】

- To confirm that the WLS performs as expected, it was installed in the 180L prototype
- If it works as intended, an improvement in the detector's energy resolution is expected
- Data acquisition is currently in progress


▲ Scintillation coincidence signal of the WLS

Conclusions

- AXEL experiment is searching for 0νββ using a high-pressure xenon gas TPC
- Low efficiency of scintillation light detection is causing a significant z mis-reconstruction
  ⇒ R&D of a novel scintillation detector by WLS plate
- Production of high-quality TPB-coated plates has been successfully established
- Performance in xenon gas are better than expected
- Currently testing whether the energy resolution can be improved by introducing the new scintillation detectors into the 180L prototype

Bibliography

[1] KamLAND-Zen Collaboration, arXiv:2406.11438
[2] Joshua R. Graybill, Chandra B. Shahi, Michael A. Coplan, Alan K. Thompson, Robert E. Vest, and Charles W. Clark, "Extreme ultraviolet photon conversion efficiency of tetraphenyl butadiene," Appl. Opt. 59, 1217-1224 (2020)