AXEL

high pressure xenon gas TPC
for neutrinoless double beta decay search

Kiseki Nakamura | Kyoto Univ.
For the AXEL group

1. AXEL project
2. Fundamental studies
3. Prototype detector
4. Future prospect
5. Summary
1. AXEL project
2. Fundamental studies
3. Prototype detector
4. Future prospect
5. Summary
**AXEL experiment**

- High pressure xenon gas TPC for $0\nu\beta\beta$ search
  - High energy resolution: **0.5% (FWHM) @2.5MeV**
    - gaseous xenon + electroluminescence
  - Large mass: **1ton** ($\phi3\times2.5m, 10atm$)
  - BG discrimination: **pixel readout** (15mm pitch)

- Similar idea as NEXT experiment
- We introduce a new idea for signal readout (ELCC)

![Graph showing energy resolution vs density]
• ELCC
  • in the cell hole, electrons are collected and accelerated, then electroluminescence photons are generated
  • photons are detected by MPPC(SiPM) in each cell

• Merit of ELCC
  • uniform response in wide area
  • rigid structure (--> large size)
What we want to observe

- $0\nu\beta\beta$ signal
  - energy: integrated FADC
  - track: waveforms (pixel readout TPC)

10 atm
Xe 100%
15 mm pitch
1 $\mu$s sampling (~1 mm)
Tracking strategy

- energy resolution 0.5% --> reject non-2.5MeV
- tracking --> reject α, γ (98%: compton)

10atm, Xe100%, 15mm pitch, 1μs sampling (~1mm)
1. AXEL project
2. Fundamental studies
3. Prototype detector
4. Future prospect
5. Summary
Electric field simulation (FEMM)

- Line of electric field are collected
- Uniformity of EL yield is 0.47% (sigma)

\[
dN_{ph}/dx = 70(E/p - 1.0)p
\]
MPPC linearity

- Check large and long pulse photon response ($\sim 10^5/5\mu s$)
- Saturation was observed
  - “simultaneous hit” and “decrease of bias voltage”
- After correction, expected residual fluctuation is 0.11%

\[
N_{\text{obs}} = \frac{p_0 N_{\text{pmt}}}{1 + k\tau + Gp_0 N_{\text{pmt}}}
\]
1. AXEL project
2. Fundamental studies
3. Prototype detector
4. Future prospect
5. Summary
Overall view

• Kyoto Univ. 3F (welcome!)

### Table

<table>
<thead>
<tr>
<th>Name</th>
<th>filter class</th>
<th>filter num</th>
<th>filter flow</th>
<th>overall flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLL25 [Matsusada]</td>
<td>10000</td>
<td>4</td>
<td>7 m³/min</td>
<td>64 times/h</td>
</tr>
</tbody>
</table>

**Gas System**

- Chamber: 10L, <10 atm

**Dimensions**

- 5m
- 2.5m
Prototype detector

- Detection volume
  - 6*6*6cm³
  - 5.7g (4atm Xe)

- Sensor
  - WLS coated MPPC x64
  - VUV-PMT x2

- Electric field
  - EL: 2.4kV/cm/atm
  - drift: 50V/cm/atm
Event sample

- waveforms of MPPC and PMT
  - EL light & scintillation light are observed

MPPC: 65MHz 12bit 2Vpp
PMT: 100MHz 14bit 2Vpp
γ-ray measurement \((^{57}\text{Co} \ 122\text{keV})\)

- Fiducial cut
  - veto region: outer 28 MPPCs

red: veto
γ-ray measurement (⁵⁷Co 122keV)

- Time dependence correction
- Impurities decrease EL gain
- Gas circulation system is now under construction
γ-ray measurement ($^{57}$Co 122keV)

- EL-gain correction
  - photon num of 30keV γ-ray for “each cell”
    - One MPPC(red) selection is too strict, so blue MPPCs are allowed
    - EL crosstalk suppression structure is under designing

![Graphs showing σ=0.065 and σ=0.016](image)

- MPPC and PTFE line of electric field

![Diagram showing EL crosstalk](image)
γ-ray measurement ($^{57}$Co 122keV)

- Hit volume correction
  - strong correlation was obtained
  - (recombination is seen?)
Energy resolution

- Four peaks are observed
- FWHMs are evaluated by Gaussian fitting

<table>
<thead>
<tr>
<th></th>
<th>Kα</th>
<th>Kβ</th>
<th>escape</th>
<th>full</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>29.8keV</td>
<td>33.6keV</td>
<td>92.3keV</td>
<td>122keV</td>
</tr>
<tr>
<td>photon #</td>
<td>6605</td>
<td>7516</td>
<td>18711</td>
<td>24710</td>
</tr>
<tr>
<td>FWHM</td>
<td>7.9%</td>
<td>8.7%</td>
<td>5.6%</td>
<td>4.7%</td>
</tr>
</tbody>
</table>
Energy resolution estimation at Q

- Estimated resolution is 1~3.6%(FWHM) @2.5MeV
  - Several factor for the target

- We plan to improve energy resolution by
  - VUV-MPPC
  - gas circulation
  - crosstalk suppress
  - etc...

- We also plan to make larger detector
Upgrades

- Long field cage
  - For 511keV $\gamma$-ray
- New VUV-sensitive MPPCs
  - instead of WLS-painted MPPC
  - operation test with $^{57}$Co seems OK
- Gas circulation
  - pump (last component) is now vacuum test
- EL crosstalk suppression
  - designing

VUV-MPPCs are installed

operation test with $^{57}$Co

Preliminary
Our goal is ....

• $0\nu\beta\beta$ discovery !!!
  • or exclude inverted hierarchy

• Expected event rate
  • 0.5 count/year/ton ($m_{\beta\beta} = 10\text{meV}$)
  • We need ton scale detector
  • BG rate requirement in ROI < ~1 count/year

<table>
<thead>
<tr>
<th></th>
<th>volume</th>
<th>mass</th>
<th>MPPC #</th>
<th>purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>current</td>
<td>0.216L</td>
<td>~10g</td>
<td>64</td>
<td>ELCC test (122keV, 511keV)</td>
</tr>
<tr>
<td>next (2016~2017)</td>
<td>~200L</td>
<td>~10kg</td>
<td>~2000</td>
<td>2.5MeV demonstration enriched $^{136}\text{Xe}$</td>
</tr>
<tr>
<td>next2 (2018~)</td>
<td>~200L</td>
<td>~10kg</td>
<td>~2000</td>
<td></td>
</tr>
<tr>
<td>future (202X~)</td>
<td>~18000L</td>
<td>~1ton</td>
<td>~31000</td>
<td>$0\nu\beta\beta$ search</td>
</tr>
</tbody>
</table>
Next prototype detector

• **Purpose**
  - energy resolution @ 2.5MeV(Q value)
  - establish large size technique
  - tracking ability
  - BG observation

• **Status**
  - readout board --> Tanaka’s poster
  - structure : designing with Geant4
  - clean room : constructed large size
  - gas system : considering safety devices
  - etc...
Most serious BG for AXEL

• γ-ray from $^{214}$Bi is our enemy
• chamber mass: 25 ton
• expected BG is 1000 cts/year

\[
R_{BG} = M \times C \times \frac{N_A}{M_{238U}} \times \frac{\ln 2}{T_{1/2}^{238U}} \times \Omega \times B \times R = \sim 1000 \text{ counts/year}
\]

- Mass $\sim 25 \times 10^6$ g
- Contamination $2.9 \times 10^{-12}$ g/g
- Avogadro # $6.02 \times 10^{23}$
- solid angle $\sim 0.1$
- branching ratio 0.0157
- photoab. ratio 0.02
- atomic weight 228
- half life $4.468 \times 10^9$
• Geant4 + diffusion
• Two blobs detected
• 1/10 reduction will be expected
  • (still remain 100 cts)
Pressurized water shield

• Concept
  • Similar structure to KamLAND-Zen
  • Thickness: 37.3mm --> 3mm (ex. EXO achieved 1.37mm)
    • or thinner thickness like balloon
  • BG will be 10 counts/year

• Plan
  • pressure test for various materials
  • construct small system
Summary

• AXEL project
  • $0\nu\beta\beta$ search using high pressure xenon gas TPC with high energy resolution, large mass and tracking ability
  • New readout idea: ELCC (electric field simulation is OK)
  • Linearity for $1e5/5\mu s$: correction fluctuation is 0.12% (OK)

• Prototype detector
  • Energy resolution: 1~3.6%(FWHM) at Q (many improvements are ongoing)
  • Long size + VUV-MPPC result will come soon (511keV)

• Future prospects
  • We started making large size detector --> Tanaka’s poster
  • $\gamma$-ray BG from $^{214}$Bi in the chamber (heaviest component) will be reduced by tracking and water shield: 1000->100->10
We measured MPPC’s linearity by using PMT as a reference

- Irradiated LED light up to $\sim 10^5/5\mu s$
- Observed saturation is slightly larger than expected from the number of pixels and recovery time. Under investigation
- After correction, expected residual fluctuation is 0.12% ($< 0.5\% : \text{target energy resolution}$)
ELCC demonstration by UV-PMT

Setup
- 1atm Xe
- UV-PMT (H3178-51Q)
- all cells are merged
- detection size: 28x28x55mm

Energy resolution (FWHM)
- 13.8% @30keV (fit right edge)
- 1.5% @2.5MeV (converted)
Voltage for 1 atm

- Drift
  - $\text{driftV}$ change small at $>30$ V/cm

- Anode
  - 8kV is enough
Linearity measurement

Result

• Slowly saturated (25mm pitch is better)

<table>
<thead>
<tr>
<th>MPPC pixel pitch</th>
<th>50μm</th>
<th>25μm</th>
<th>VUV 50μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>photon# to keep linearity</td>
<td>$1.5 \times 10^4$</td>
<td>$2.5 \times 10^4$</td>
<td>$1.5 \times 10^4$</td>
</tr>
<tr>
<td>$N_{pixel}$</td>
<td>3600</td>
<td>14400</td>
<td>3600</td>
</tr>
</tbody>
</table>

• After correction, fluctuation is 0.12% (< 0.5% : aim of Eres)
Linearity measurement

- Photon rate per pixel: \( k[1/(\text{pixel} \cdot \text{s})] = \frac{N_{\text{true}}}{N_{\text{pixel}} \cdot \Delta t} \)

- Average gain: 
  \[
  g = \int_0^\infty ke^{kt} g_0 (1 - e^{-t/\tau}) \, dt = \frac{g_0}{1 + k\tau}
  \]
  - Probability to hit after \( t \) sec
  - Gain after \( t \) sec
  - \( \tau \): recovery time

- Observed photon#: \( N_{\text{obs}} = \frac{N_{\text{true}}}{1 + k\tau} \)

- Fluctuation of correction:
  \[
  \frac{\Delta N}{N} = \frac{N_{\text{true}} - N_{\text{obs}}}{N_{\text{true}}} = \sqrt{\frac{\tau}{N_{\text{pixel}} \cdot \Delta t}} = \sqrt{\frac{25\text{ns}}{3600 \cdot 5\mu\text{s}}} = 0.0012
  \]
Prototype detector: gas system

- Chamber
- Vacuum pump
- Getter
- Micro torr
- Flow meter
- Circular pump
- Regulator
- Pressure gauge
- Pressure relief valve (10 atm)
- Valve
- Reuse Xe
- LN2
- Filling new Xe
- Filling reuse Xe
- Returning Xe

Materials and Components:
- Ar
- Xe
- [API] API-GETTER-I-Re AG-100 (Xe.He)
- [saes] MC1-902F
- [Bronkhorst] EL-FLOW F-111CM-40K-AAD-88-K
- [CHUGIKEN KOGYO] NKCV1S1P3208-90
- [API] API-GETTER
High voltage optimization

- Electric field
  - $E_{\text{anode}} = 2.4\text{kV/cm/atm}$
  - $E_{\text{drift}} = 50\text{V/cm/atm}$
- correction efficiency (by FEMM) is 100%
Data acquisition

- record waveform (64ch)
- 65MHz 12bit 2Vpp
electronics

- low pass filter (64ch)
  - large time constant: 50msec
  - large capacitance: 1uF
  - for large and long pulse
\( E_{\text{anode}} \) dependence

- Linear dependence --> OK
- We can supply higher \( E_{\text{anode}} \)
Yield calculation

\[ \alpha = P_{\text{coll}} \times Y \times \Omega \times P_{\text{trans}} \times \frac{1}{2} \times \text{PDE} \]

- \( \alpha \) : detected EL photon# per electron (measured)
- \( P_{\text{coll}} \) : collection efficiency of electric field line (100%)
- \( Y \) : Yield of EL (calculated)
- \( \Omega \) : solid angle of EL photon to MPPC (12.9%)
- \( P_{\text{trans}} \) : WLS translation efficiency 50%
- \( 1/2 \) : translated photon direction (up/down)
- \( \text{PDE} \) : PDE of MPPC (35%)
Garfield++

- finer pitch is better (but ch# increase)
Tracking demonstration ($\alpha$-ray)

- Detect EL light
  - OK!
- Track width is too large?
  - large $\text{Diff}_{\text{tra}}$ --> High Pressure
  - blurred at WLS --> UV-MPPC

$\text{gas} : \text{Xe} 1\text{atm}$

$E_{\text{anode}} = 1.6\text{kV/0.5cm}$

$E_{\text{drift}} = 0.4\text{kV/6cm}$

$\text{Diff}_{\text{tra}} = 0.34\text{cm/Vcm}$

\[\alpha\text{-src (Toritan)}\]
Readout electronics

- For 1 ton detector, MPPC # will be 50000
- AFTER chip (ASIC) 72ch 511 sampling
- developing board for AFTER

![Diagram of the readout electronics system]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels</td>
<td>72</td>
</tr>
<tr>
<td>Samples per channel</td>
<td>511</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>2 V / 10 MIPs on 12 bits</td>
</tr>
<tr>
<td>MIP charge</td>
<td>12 fC to 60 fC</td>
</tr>
<tr>
<td>MIP/Noise ratio</td>
<td>100</td>
</tr>
<tr>
<td>Gain</td>
<td>4 values from 4 mV / fC to 18 mV / fC</td>
</tr>
<tr>
<td>“Detector” capacitor range</td>
<td>20 pF -30 pF</td>
</tr>
<tr>
<td>Peaking Time</td>
<td>100 ns to 2 μs (16 values)</td>
</tr>
<tr>
<td>INL</td>
<td>1% 0-3 MIPs ; 5% 3-10MIPs</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>1 MHz to 50 MHz</td>
</tr>
<tr>
<td>Readout frequency</td>
<td>20 MHz to 25 MHz</td>
</tr>
<tr>
<td>Polarity of detector signal</td>
<td>Negative (T2K) or Positive</td>
</tr>
<tr>
<td>Test</td>
<td>1 among 72 channels or all</td>
</tr>
</tbody>
</table>
Comparison of $0\nu\beta\beta$, e and $\alpha$

- Event topology by tracking
  - $\alpha$ BG is well rejected
  - $\gamma$ BG with 2.5MeV photoelectric absorption is difficult to reject perfectly.
  - (multi site events such as Compton scattering can be rejected)

![Graphs of $0\nu\beta\beta$, electron, and alpha events](image)
Comparison of $0\nu\beta\beta$, e and $\alpha$

- Event topology by tracking
  - $\alpha$ BG is well rejected
  - $\gamma$ BG with 2.5MeV photoelectric absorption is difficult to reject perfectly.
  - (multi site events such as Compton scattering can be rejected)

View scales are different. Cell size is same.
Rate of $^{214}$Bi $\gamma$-ray

- Attenuation length of 2.5MeV $\gamma$-ray
  - 140cm in 30atm Xe -> self shielding is not effective
  - 20cm in water -> external BG stop by water shield

- Materials of detector must be checked
  - Vessel is the most heavy component (10ton : copper)
  - EXO uses clean copper for vessel : $U < 5$ppt 95% U.L.

\[ R_{BG} = M \times C \times \frac{N_A}{M_{238U}} \times \frac{\ln 2}{T_{1/2}^{238U}} \times \Omega \times B \times R = 643 \text{ counts/year} \]

- Mass $\sim 10^6 \text{ g}$
- Contamination $5 \times 10^{-12} \text{ g/g}$
- Avogadro # $6.02 \times 10^{23}$
- solid angle $\sim 0.1$
- branching ratio 0.0157
- photoab. ratio 0.02

- atomic weight 228
- half life $4.468 \times 10^9$
How to deal with $^{214}\text{Bi}$?

• Improve energy resolution
  • Energy difference between 0νββ and γ from $^{214}\text{Bi}$ is 0.44%
  • Intrinsic energy resolution is 0.25%
• Put some shield “in” the vessel
  • pressure vessel become huge
• Make clean vessel
  • purifying copper
• Make light vessel
  • titanium is strong and light (NEXT group’s approach)
  • need 2 ton --> still need purification
• --> we noticed rejection of high energy γ is not so easy
Stopping power

- Attenuation length of 2.5MeV $\gamma$-ray
  - 140cm in 30atm Xe
  - 20cm in water

- Shielding
  - Xe self shielding is not effective
Electric Field and electron drift

@ E=1.5kV/cm, p=30 bar
Drift velocity 0.96m/ms
- Possibly add H₂, N₂ or He to increase the drift velocity.
  - It will also reduce diffusion.
  - It will also reduce light yield diffusion after 1m drift
- transverse : 6mm
- longitudinal : 2.7mm
Directional dark matter Search

Approaches to directionality detection (3):
Columnar recombination and Inferring direction without track image

- Measure recombination rate from scintillation yield and ionization yield
- We are planning to apply magnetic field to enhance the recombination yield for one direction

Case 1: More Recombination
Case 2: Less Recombination

Concept by Dave Nygren, LBNL
Recombination measurement

• Purpose
  • measure recombination and ionized signal (5.4MeV $\alpha$)
  • test putting magnetic field
Recombination measurement

• Status
  • construction just started