Study on $^{10}$C Tagging Efficiency for KamLAND2-Zen

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1. Background of this study
   - KamLAND-Zen Experiment
   - Future Plan: KamLAND2-Zen Experiment

2. Problem in KamLAND2-Zen
   - $^{10}$C background
   - How to handle the problem

3. Tag efficiency of neutron and $^{10}$C
   - Neutron tag efficiency
   - $^{10}$C tag efficiency

4. Summary
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Neutrino-less double beta decay ($0\nu\beta\beta$) search of $^{136}\text{Xe}$

KamLAND-Zen Experiment

$T_{1/2}^{0\nu} > 1.06 \times 10^{26}$ [yr] (90% C.L.)

$\langle m_{\beta\beta}\rangle < 61 -165$ [meV] (90% C.L.)

Need to improve energy resolution → KamLAND2-Zen Experiment
• High Quantum Efficiency PMT (HQE-PMT)
  light yields × 1.9
• Light collection mirror
  light yields × 1.8
• New liquid scintillator
  light yield × 1.4

Total light yields × 5
  - Energy resolution (σ) : 4.2% → ~ 2% @ Q-value
  - 2νββ background : ~1/100

Others
  - Scintillation mini-balloon for 214Bi tag
  - New data acquirement circuit (MoGURA2)

Aim to $<m_{ββ}> \sim 20$ [meV] w/ 1000 kg Xenon in 5 yr
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$^{10}\text{C Tag}$

- Improvement of energy resolution ($2\nu\beta\beta$)
- Scintillation mini-balloon ($^{214}\text{Bi}$ can be tagged)

$\rightarrow$ Main background of KamLAND2-Zen = $^{10}\text{C}$

$^{10}\text{C}$ ... Cosmic ray muon spallation product

1. Muon
2. Neutron capture
3. $\beta^+$ decay of $^{10}\text{C}$

Tag w/ triple delayed coincidence

Tag efficiency: $64\pm4\%$
Miss of neutron events

- Tag efficiency: ~54%
- Discriminator does not work
- Data acquisition stuck

Neutron detection will be more difficult in KamLAND2 (light yield ↑)

→ Need prevention of overshoot and afterpulse
Using Venetian Blind PMT

Candidate PMT = 20”Box and Line type (R12860 HQE):
- Good time and light collection property
- High afterpulse rate

Venetian Blind PMT is superior in terms of neutron detection
New trigger mode

- Mount trigger mode dedicated to neutron detection (Only after muon)
  → Differential hit + Local hit trigger scheme

Differential hit detection

Threshold is set in terms of differential

![Diagram showing differential waveforms and time differences between PMTs in all detector and local area.]

Can detect signals under baseline shift

New trigger scheme: Local hit scheme

- PMTs in all Detector: Hit time difference > 40 ns
- PMTs in local area: Hit timing difference = ~ 20 ns

By setting threshold in terms of the # of local hit (determined w/ the # of hit PMTs in local area), time window for hit detection can be shorter. → influence of afterpulse become smaller

Optimized parameters in previous study (assumption: 10000 p.e. incident)
- Threshold for local hit = 14 ch/16ch in local area
- Threshold for data acquisition = 65 local hit/118 local hit

Muon events in KamLAND2

Light incident to PMTs in muon event in KamLAND2 will be more than 10000 p.e.

Distribution of light incident to each PMTs in Muon events(KamLAND2)

- More influence of overshoot and afterpulse to neutron detection than expected in previous study
- Afterpulse might disturb event reconstruction

Neutron tag efficiency = Neutron detection efficiency \times Neutron reconstruction efficiency

Need more study of new trigger scheme
Purpose

To evaluate new trigger mode

• to investigate neutron tag efficiency

  (Neutron tag efficiency = Neutron detection efficiency × Neutron reconstruction efficiency)

- Consider more than 10000 p.e. incident

- Consider influence of afterpulse to event reconstruction

- Check the case that **30% of PMTs** are Venetian Blind type

  ⊳ T.T.S. and light collection efficiency are inferior to those of Box and Line type
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Neutron detection efficiency

Simulation of local hit probability with real HQE-PMTs waveform

- LED: $1 \times 10^4, 2 \times 10^4, 3 \times 10^4, 4 \times 10^4, 5 \times 10^4, 7 \times 10^4, 9 \times 10^4$, p.e.
- PLP: ~3 p.e.

- Checked two cases
  - 100% Box and Line PMT
  - 30% Venetian Blind + 70% Box and Line
Trigger issues on neutron events

- Trigger on afterpulse converges within about 20 μs (not data acquirement stuck)

All neutron events data is recorded

Neutron tag efficiency = Neutron detection efficiency × Neutron reconstruction efficiency

→ Neutron tag efficiency is determined by reconstruction efficiency

Simulation of reconstruction considering afterpulse rate is needed.
Rate of afterpulse following muon event

- Checked afterpulse rate in non-LASER region of acquired waveform

**Low Energy Muon Event**

- Box and Line
- Venetian Blind

**Middle Energy Muon Event**

- Box and Line
- Venetian Blind

**High Energy Muon Event**

- Box and Line
- Venetian Blind

Venetian Blind PMT: Lower afterpulse assuming reconstruct
- Box and Line case
  - w/ Box and Line PMT
- Box and Line + Venetian Blind case
  - only w/ Venetian Blind PMT
Event reconstruction efficiency (Box and Line)

- Imitated hit data of neutron events in KamLAND2 with data of $^{60}$Co at center of KamLAND
- Checked reconstruction efficiency after adding hit data of fake signal artificially

**Event reconstruction with Box and Line PMT**

- **Afterpulse rate : 0 MHz**
  - Entries: 2767
  - Efficiency: 100.00%

- **Afterpulse rate : 10 MHz**
  - Entries: 2753
  - Efficiency: 99.49%

- **Afterpulse rate : 12 MHz**
  - Entries: 1762
  - Efficiency: 63.68%

- **Afterpulse rate : 13 MHz**
  - Entries: 662
  - Efficiency: 23.92%

- **Afterpulse rate : 14 MHz**
  - Entries: 115
  - Efficiency: 4.16%

- **Afterpulse rate : 15 MHz**
  - Entries: 8
  - Efficiency: 0.29%
Event reconstruction efficiency (Venetian Blind)

- Light collection and T.T.S. are considered

**Event reconstruction with Venetian Blind PMT**

- **Afterpulse rate : 0 MHz**
  - Entries : 2767
  - Efficiency : 100.00%

- **Afterpulse rate : 10 MHz**
  - Entries : 2599
  - Efficiency : 93.93%

- **Afterpulse rate : 12 MHz**
  - Entries : 1353
  - Efficiency : 48.90%

- **Afterpulse rate : 13 MHz**
  - Entries : 570
  - Efficiency : 20.60%

- **Afterpulse rate : 14 MHz**
  - Entries : 202
  - Efficiency : 7.30%

- **Afterpulse rate : 15 MHz**
  - Entries : 56
  - Efficiency : 2.02%
Neutron tag

# of neutron tagging after muon w/ new trigger mode

Detectable neutrons/ns

$\times 10^{-6}$:

# of detected neutron after muon

$\mu$T from muon

Entries: 73743
Mean: 251.7
RMS: 148.2

Only Box and Line
Box and Line + Venetian Blind
Ideal Curve

$dT \sim 450 \mu$s

dT ~ 40 \mu$s

All the neutrons can be tagged within $dT \sim 40 \mu$s even after muons which produce $^{10}$C
Neutron tag efficiency $p_E$

- Present: $p_E = 54\%$
  - new data acquisition system
  
  
  $p_E = 88.80 \pm 2.00\%$ (only Box and Line PMT)

  
  
  - new data acquisition system + Venetian Blind PMT

  
  
  $p_E = 92.28 \pm 1.83\%$ (Box and Line + Venetian Blind PMT)

- Neutron detection efficiency will be improved by new data acquisition system
- Efficiency will be enhanced with Venetian Blind PMT

$^{10}$C Tag efficiency $P$

present: $P = 64\%$ →

\[
\begin{cases} 
  P = 98.75 \pm 0.03\% & \text{(only Box and Line)} \\
  P = 98.82 \pm 0.02\% & \text{(Box and Line + Venetian Blind)}
\end{cases}
\]
## Backgrounds in 5 years measurement

<table>
<thead>
<tr>
<th>KamLAND-Zen</th>
<th>KamLAND2-Zen</th>
</tr>
</thead>
<tbody>
<tr>
<td>(calculated by result of KamLAND-Zen 400)</td>
<td>(w/o new data acquirement system)</td>
</tr>
<tr>
<td><strong>BG</strong></td>
<td><strong>events[/5 yr]</strong></td>
</tr>
<tr>
<td>2νββ</td>
<td>36.9</td>
</tr>
<tr>
<td>10C</td>
<td>20.8</td>
</tr>
</tbody>
</table>

**Considering new data acquirement system**

### Box and Line

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<th><strong>BG</strong></th>
<th><strong>events[/5 yr]</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>2νββ</td>
<td>2.77</td>
</tr>
<tr>
<td>10C</td>
<td>1.79</td>
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</tbody>
</table>

### 70% Box and Line + 30% Venetian Blind

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<th><strong>events[/5 yr]</strong></th>
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<tbody>
<tr>
<td>2νββ</td>
<td>3.41</td>
</tr>
<tr>
<td>10C</td>
<td>1.69</td>
</tr>
</tbody>
</table>

→ increase because of less light collection

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**Due to new data acquirement system, 10C BG will decrease dramatically**

(Using only Box and Line type is better in terms of total background amount)

In 5 years measurement …

- Limit on half-life of 0vbb: \( T_{1/2}^{0ν} > 1.89 \times 10^{27} \) [yr] (90% C.L.)
- Limit on Majorana effective mass: \(<m_{\beta\beta}> < 14.5 - 39.0 \) [meV] (90% C.L.)

- \(^{214}\text{Bi}\) can be tagged
- \(^{8}\text{B}\) solar \(\nu\)
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Summary

- KamLAND2-Zen = Future plan for KamLAND-Zen (0νββ search)
  - It is concerned that detection efficiency of neutron and $^{10}$C tag efficiency will become worse

- Property of Venetian Blind PMT (R3600 HQE) was studied under intense light incident
  - Revealed that V.B. PMT is effective to improve neutron detection efficiency

- New trigger scheme for neutron detection was studied
  - Incident in KamLAND2 was reproduced
  - Influence of fake signals to event reconstruction was considered
  - Effectiveness of Venetian Blind PMT was also investigated

- Neutron tag: $54\% \rightarrow 88.80 \pm 2.00\%$ (B&L), $92.28 \pm 1.83\%$ (B&L+VB)
- $^{10}$C tag: $64\% \rightarrow 98.75 \pm 0.03\%$ (B&L), $98.82 \pm 0.02\%$ (B&L+VB)