Development of pre–shower counter for time calibration of MEG II liquid xenon detector

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On behalf of MEG II collaboration
The University of Tokyo
Liquid Xenon Detector

- Detects $\gamma$ energy, position and timing
- Liquid xenon scintillator and photon sensors
- Replaced 216 PMTs with 4092 MPPCs
time resolution $67\,\text{ps} \to 50\,\text{ps}$

25aK206 : In-beam performance of MEG II liquid Xe detector (Shinji Ogawa)
Calibration using Charge EXchange

- A calibration run for LXe detector planned this year
- $\pi^0$ is produced in
  \[ \pi^- p \rightarrow \pi^0 n \]
  - Monochromatic energy $\gamma$-ray selecting back-to-back event from $\pi^0 \rightarrow \gamma \gamma$
  - Similar energy with signal $\gamma$
- Pre-shower counter for a timing measurement
- BGO crystal for energy and position measurements
Pre-shower Counter @MEG II

Pre-shower counter @MEG
- 2 plastic scintillators readout with fine mesh PMTs
- Final time resolution 72 [ps] is worse than that of LXe (50 [ps])

New pre-shower counter
- 2 plastic scintillators readout with SiPMs

MEG II Timing Counter study
- More light yields \( \rightarrow \) more SiPMs
- Fast risetime \( \rightarrow \) series > parallel connection

Topics of this talk
- Investigations to decide the counter design
  - The number of SiPMs and their connection
  - Size and shape of a scintillator
Comparison of SiPM Connection Scheme
Setup to Test SiPM Connections

Test counter
- Plastic scintillator: BC420, Saint-Gobain
  - Attenuation length: 140 cm
- MPPC: S13360-3050PE, Hamamatsu Photonics
  - 3 x 3 [mm²] photosensitive area
  - $V_{br} \sim 52$ [V]
- Reflector: ESR2 (Polyester)
- Optical grease: 6262A, OHYO KOKEN KOGYO CO.

Trigger counter
- Plastic scintillator: BC422 (5 x 5 x 5 mm³)
- MPPC: S10362-22-050C

Readout Scheme
- Pole zero cancellation
- MPPCs
- Amp
- Waveform digitizer

Change the number of MPPCs used or connection

Resolution was calculated by subtracting the time of one side $t_1$ from the other side $t_2$

$$\sigma_{counter} = \frac{\sigma_{t_1 - t_2}}{2}$$
Difference of Single Photoelectron Waveform Caused by Series Connection

As more MPPCs are connected in series, capacitance gets smaller.

- faster risetime
- height becomes lower

$\rightarrow$ S/N is not good when there are too many MPPCs connected in series
MPPC Connection Effect to Time Resolution

- Tested two other connections:
  - individual readout: twice capacitance
  - partly parallel: 4 times capacitance
- Measurements show improvement of time resolution starts to saturate when about 4 MPPCs are connected
  → Individual readout and partially parallel connection are better when the number of MPPCs are more than 8

Decided to use 4 series connection
(4 series × 4 readout × 2 sides)
Comparison of different Scintillator Sizes
Comparison of Time Resolution with Different Scintillator Sizes

- Detected light yield is the most important factor to get good time resolution.
- According to simulation, light yield of a scintillator doesn’t depend on scintillator size but on SiPM coverage→ Suggests time resolution is the same.
- Measurements proved that

Decided to use 92 [mm] scintillator for larger acceptance.
Position Scan
Light Yield Position Dependence

• When RI is far from the center, light yields of some channels are too small while other channels saturate depending on their positions
  → less statistics & worse S/N
  → large position dependence of time resolution

• According to simulations, if the length of scintillator is longer, the light yield difference is less in the necessary region.
Setup for New Scintillator

- New scintillator
  - EJ-230 (equivalent to BC-420)
  - Attenuation length 120 cm
  - 80 \times 175 \times 5 \text{ mm}^3
- MPPCs
  - 4 series \times 4 channels \times 2 \text{ sides}
  - Attached to PCBs
- Reflector: ESR (Polyester)

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Risetime [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-420 (92 \times 92 \times 5 \text{ mm}^3)</td>
<td>2.017</td>
</tr>
<tr>
<td>EJ-230 (80 \times 175 \times 5 \text{ mm}^3)</td>
<td>1.055</td>
</tr>
</tbody>
</table>

Faster risetime is supposed to make time resolution better.
Time Resolution

- Time resolution got much better: 42 [ps] → 28 [ps] @ the center (Vover = 7 [V])
- Smaller position dependence of time resolution: 60 - 100 [ps] → 27 - 32 [ps]

←smaller position dependence of light yields

Decided to use a scintillator whose size is 80 × 175 × 5 [mm³]
Summary

• The pre-shower counter for LXe detector timing calibration will be upgraded based on MEG II Timing Counter design

• Decided the counter design
  • 4 series connected MPPCs readout by 4 channels on each side
    ➢ fast risetime and more MPPCs
    ➢ Pulse height reduction caused by series connection
  • 80 × 175 × 5 [mm³] scintillator
    ➢ time resolution is independent of scintillator size if coverage is equal
    ➢ large size for large acceptance
    ➢ a longer scintillator for smaller position dependence

• Achieved 28 [ps] time resolution at the center with small position dependence (< 5 [ps])
Prospect

• Finish construction of pre-shower counter
• Measurements with the counter
  • with electronics used for operation
  • with γ source this summer
• Charge Exchange calibration run on Nov.
Back up
MEG II Experiment

Upgraded from MEG
- $\mu^+$ beam stopping rate
  $3 \times 10^7 \text{ } /\text{s} \rightarrow 7 \times 10^7 \text{ } /\text{s}$
- Improved efficiency and resolution of each detector

Expected sensitivity
$4.2 \times 10^{-13} \rightarrow 4 \times 10^{-14}$
Calibration using Charge EXchange

- Pre-shower counter for a timing measurement
- BGO crystal for energy and position measurements

BGO crystal
- 4 × 4 arrayed
- Read out with fine mesh PMTs

BGO crystals
46 × 46 × 200 mm³ each
Previous Research about MEG II TC


Reached 50 [ps] resolution
- 40 × 90 × 5 [mm³], BC422 scintillator
- 6 series SiPMs (ASD-NUV3S-P-50)

To achieve better resolution
- High light yield → more MPPCs
- Fast rise time → series > parallel because of smaller capacitance
MPPC Selection

MPPCs connected in series or parallel must have similar characteristics.

• I-V measurement for 100 MPPCs
• Choose 36 MPPCs which have similar I-V curves
MPPC Selection

- I-V measurement for 100 MPPCs
- Fit the curve to the function

\[ f(V) = \begin{cases} 
  c & V < V_{br} \\
  a \cdot (V - V_{br})^2 + c & V > V_{br} 
\end{cases} \]

- Made clusters considering \( V_{op}, I_{op}, a \)
A signal is found by searching a peak. Some events include a signal in noise calculation area. Therefore, these events should be cut.
Event Selection

![Diagram of Event Selection](image)

- **calculation area for baseline RMS**
- **signal**
- **signal**
Comparison of Series/Parallel Connection

Checked difference between series and parallel connection. Resolution of series connection is superior to that of parallel as expected.

Series
- Resolution improves as more MPPCs are connected.

Parallel
- Resolution doesn’t improve with many MPPCs due to large capacitance.
Risetime w/o PZC

- Independent of a scintillator size
- Decrease from 2 MPPCs to 4 MPPCs, but become almost stable after that
  → time response of the scintillator?
Height Difference of Single Photon Caused by Series Connection

- Height is apparently reduced by series connection
- Decrease tendencies are not the same between w/and w/o PZC
Measured Result for Light Yield

- Heights corrected by coverage are almost the same among the three
  → Consistent with the simulation
Light Yield Simulation

92 × 92 × 5 [mm$^3$] 80 × 175 × 5 [mm$^3$]

• If the RI is on the nearest position to one side (4, 10), the highest light yields is about 9 times higher than the lowest one.

• The difference gets smaller as the RI gets far from the side MPPCs attach to.

• If the length of scintillator is longer, the light yield difference is less.

→ Decided to use a scintillator whose size is 80 × 175 × 5 [mm$^3$]

JPS Spring Meeting 2018 (25aL401-5)
Time Resolution Improvement

- Risetime is much faster
- S/N became lower overall.
  - Height became relatively low.
  - Equivalent noise level.
Spec Sheets

Eljen Technology

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>EJ-228</th>
<th>EJ-230</th>
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</thead>
<tbody>
<tr>
<td>Light Output (% Anthracene)</td>
<td>67</td>
<td>64</td>
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<tr>
<td>Scintillation Efficiency (photons/1 MeV e(^{-}))</td>
<td>10,200</td>
<td>9,700</td>
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<td>Wavelength of Maximum Emission (nm)</td>
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<td>391</td>
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<td>Light Attenuation Length (cm)</td>
<td>-</td>
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<td>Rise Time (ns)</td>
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<td>Decay Time (ns)</td>
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<td>Pulse Width, FWHM (ns)</td>
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<td>H Atoms per cm(^3) (x10(^{22}))</td>
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<td>5.15</td>
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<td>C Atoms per cm(^3) (x10(^{22}))</td>
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<tr>
<td>Electrons per cm(^3) (x10(^{23}))</td>
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<tr>
<td>Density (g/cm(^3))</td>
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<td>1.023</td>
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Saint Gobain

<table>
<thead>
<tr>
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<th>BC-418</th>
<th>BC-420</th>
<th>BC-422</th>
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<td>Scintillation Properties</td>
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<tr>
<td>Light Output, %Anthracene</td>
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<td>64</td>
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<td>Rise Time, ns</td>
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<td>Decay Time (ns)</td>
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<td>Pulse Width, FWHM, ns</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
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<tr>
<td>Wavelength of Max. Emission, nm</td>
<td>391</td>
<td>391</td>
<td>370</td>
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<tr>
<td>Light Attenuation Length, cm*</td>
<td>NA**</td>
<td>140</td>
<td>NA**</td>
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<tr>
<td>Bulk Light Attenuation Length, cm</td>
<td>100</td>
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<tr>
<td>Atomic Composition</td>
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<tr>
<td>No. H Atoms per cc (x10(^{22}))</td>
<td>5.21</td>
<td>5.21</td>
<td>5.19</td>
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<td>No. C Atoms per cc (x10(^{22}))</td>
<td>4.74</td>
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<td>Ratio H:C Atoms</td>
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<td>1.100</td>
<td>1.102</td>
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<tr>
<td>No. of Electrons per cc (x10(^{23}))</td>
<td>3.37</td>
<td>3.37</td>
<td>3.34</td>
</tr>
</tbody>
</table>

*The typical 1/e attenuation length of a 1x20x200cm cast sheet with edges polished as measured with a bialkali photomultiplier tube coupled to one end.

** Scintillator recommended for use in small sizes; therefore, the 1/e attenuation length values are not applicable.
Time Resolution

- Better resolution near the center ⇐ Height
- 27 ~ 32 [ps]
Position Dependence of Each Channel

- Time resolution of each channel got better overall and its position dependence became less comparing to the smaller scintillator.
- Position dependence of height also smaller.
Mean Time

- Faster near the center
- X dependence is smaller near the center
- Y asymmetry → scintillator, MPPCs?
Mean Time Reproducibility Check

$y = 39 \text{ mm}$

- Measured again rotating the scintillator by 180 degree
- Mean time changes in $\sim 20 \text{[ps]}$
  - Not dependent on scintillator position and MPPCs
  - No reproducibility

$y = -39 \text{ mm}$

$\Rightarrow$ Reattachment of MPPCs and a scintillator?
Mean Time Reproducibility Check

- Repeated the measurement w/ nothing in in-between
- Mean time is stable during 5 measurements
  - Reattachment of MPPCs and a scintillator may affects mean time
  - Should be measured after attaching them w/ optical cement
Light Yield Position Dependence

- When RI is far from the center, light yields of some channels are too small depending on their positions
  - less statistics & worse S/N
  - large position dependence of time resolution

- The light yield difference got smaller as the RI gets far from the side MPPCs attach to.

- According to simulations, if the length of scintillator is longer, the light yield difference is less when RI is put on the same distance from the center.
Light Yield Simulation

- Even if the length of scintillator is longer, the light yield difference is large if the RI is near to one side. → Small position dependence can be limited to an area near the center.
Light Yield Simulation

92 × 92 × 5 [mm³]  

46 × 92 × 5 [mm³]

- If the width of scintillator is wider, the light yield difference among MPPCs is larger.  
  Wider scintillator can have larger position dependence.
How to mount a scintillator
Two scintillator plates + lead plate

Second layer

Lead plate
(100 x 110 x 5 mm³)

(Total thickness: 23mm
Gap between BGO and COBRA > 40mm)