MEG II 実験液体キセノン検出器用MPPCに対して低温環境が与える影響の評価

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On behalf of MEG II collaboration
The University of Tokyo
Feb. 17th, 2020
Introduction
  • The motivation of searching $\mu \rightarrow e\gamma$
  • Overview of MEG II
  • Liquid xenon photon detector

MPPC
  • VUV-sensitive MPPC
  • The mechanism of VUV detection
  • MPPC PDE decrease
  • Surface damage by VUV light

Measurement of PDE decrease
  • Outline
  • Setup
  • Result
  • Summary
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The motivation of searching $\mu \rightarrow e\gamma$

- Neutrino oscillation was discovered (1998)
  - Shows that neutrinos have mass and mixing

- $\mu \rightarrow e\gamma$ in the standard model
  \[
  Br(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 \approx 10^{-54}
  \]
  - Cannot be observed

- $\mu \rightarrow e\gamma$ in a new physics e.g. SUSY GUT
  - Assume unknown heavy particle
  \[
  Br(\mu \rightarrow e\gamma) = \mathcal{O}(10^{-12}) - \mathcal{O}(10^{-14})
  \]
  - Can be observed
Overview of the MEG II experiment at Paul Scherrer Institut

- The world’s most intense $\mu$ beam $7 \times 10^7 \mu$/sec
- Muons are stopped at the target
- Two-body decay

- The photon energy, interaction point position and time are measured by LXe
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Liquid xenon photon detector (LXe)

- Liquid xenon to measure 52.8MeV photon
- Detect the scintillation ($\lambda = 175\text{nm}$)
- 4092 MPPCs, 668 PMTs at 165K
- Energy and position resolutions will be improved as compared with MEG by a factor of two
- Under commissioning since 2017
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VUV-sensitive MPPC (SiPM)

- SiPM is a high-performance photon detector
- VUV-sensitive MPPC has been newly developed for MEG II
- Operational at low temperature (165K)
- Photon detection efficiency (PDE) >15% at $\lambda = 175\text{nm}$
- Large sensitive area ($12 \times 12 \text{ mm}^2$)
The mechanism of photon detection

● General SiPM
  • Depletion layer: p-n junction
  • Incoming photons generate electron-hole pairs
  • Reverse voltage is larger than a threshold
    → “Geiger mode”
  • In geiger mode, carriers make other carriers
    → Number of electron-hole pairs increase exponentially (avalanche multiplication) to make a signal
  • Insensitive to VUV
    → VUV stops near the surface
    → Visible light reach the deep part

● VUV-sensitive MPPC
  • Remove the protection coating (epoxy)
  • Thin down the contact layer
VUV-sensitive MPPC PDE decrease

- Alpha ray sources are in the detector → Produce VUV scintillation light
- PDE = \( \frac{N(\text{photon})_{\text{observed}}}{N(\text{photon})_{\text{expected}}} \) ∼ 8%
  → much lower than that measured in Lab(>15%)

- Degradation of MPPC VUV-sensitivity
  → quite fast ∼0.05%/hour
  (under MEG II beam intensity \( 7 \times 10^7 \mu/\text{sec} \))
- MEG II DAQ time (design) : 140 days/year, 3 years
  → This degradation is not negligible

- A possible cause: Gamma, Neutron irradiation
  → In lab test, no effect on PDE was observed
  (at room-temp)
Surface damage by VUV light

- Electron-holes are generated in SiO\textsubscript{2} by VUV light
- Holes are trapped at interface SiO\textsubscript{2}-Si
- The electric field near the boundary of the two surfaces will be reduced by the holes
  → Collection efficiency will be reduced
- Degradation seems accelerated at low temperature
  → Holes hardly move

Electron-holes are generated by VUV light in SiO\textsubscript{2}, which then trap at the interface SiO\textsubscript{2}-Si. This reduces the electric field near the boundary, leading to a decreased collection efficiency. At low temperatures, degradation seems accelerated as holes hardly move.
Surface damage by VUV light

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Outline

- To survey the effect of low temperature on the PDE decrease
  - Compare the PDE decrease at room temperature and low temperature
- To induce and monitor the PDE decrease
  - Irradiate a MPPC
  - Read current with no bias voltage
  (in previous research, correlation between current and PDE was observed)
- Xe flash lamp as a irradiation source
  - To irradiate with short-wavelength light (~175nm)
Setup

- Make vacuum in the chamber, for insulation
- Wire carries low temperature from refrigerator
- \(-240\text{K}, \text{around the MPPC}\)
  → Could not reach the LXe temp(165K)

- MPPC is irradiated through quartz window
  → Distance: 5cm
- Read 1 chip current (MPPC has 4 chip)
  → HV=0V

![Diagram of setup](image)
Setup

1ch current readout
HV=0V

Trigger for Xe-lamp
MPPC
Xe-lamp

Black sheet for safety

Chamber
Result (HV=0V)

- Irradiated one MPPC (low-temp → room-temp)

[Graph showing the current decay over irradiation time with two temperature conditions: room-temperature (~296K) and low-temperature (~240K). The graph indicates a readout problem after 38h.]
Result (HV=0V)

- Decrease of current was observed both at low-temp and room-temp
  → This might means PDE decrease
- The decrease level of low-temperature is smaller than room-temperature
  → Contrary to expectation
- The result includes the entire wavelength region
  → Different from VUV irradiation
- The temp (~240K) is much higher than LXe temp (165K)
Summary

Motivation

PDE degradation of the MPPC was observed in LXe photon detector

• PDE decrease by VUV irradiation at room-temp was slower than in LXe photon detector
  → We measured at low-temp

• Gamma, Neutron irradiation has no effect on PDE in previous research at room-temp
  → Cannot exclude the possibility that the irradiation damage (Gamma, Neutron) at low-temp is different from room-temp

Measurement

Room temp(~296K) vs Low temp(~240K)

• Could not reach the LXe temp(165K)
  → Improve the setup

• Contrary to expectations, current decrease at low temp was smaller
  → We do not know the reason
  → The possibility that we did not measure the PDE decrease for VUV light (Xe-lamp has other wave length)
  → We should measure the charge for VUV light using filters
Backup slides
MPPC PDE Decrease

![Graph showing the decrease in PDE over irradiation time for different years: 2017, 2018, and 2019. The x-axis represents the irradiation time at 7 x 10^7 μs/days, and the y-axis represents the PDE.]
For VUV light detection, precise control of MPPC’s protection layer and absorption region is required.

Generated photo-electrons excited by VUV light are transported to avalanche region by electric field. To obtain higher carrier collect efficiency, defect-less device is required.
Result (HV=4V)

- 240K, around the MPPC
- Total irradiation time : ~10h
- When bias voltage are supplied, low-temperature current seems to decrease
Result (HV=0V)

![Graph showing current decay over irradiation time for room-temperature (~296K) and low-temperature (~240K)]

- Current [a.u.]
- Irradiation time
- Room-temperature (~296K)
- Low-temperature (~240K)
Possible Cause

- **Surface damage by VUV-light**
  - Electron-hole pair generated in SiO₂ by VUV light
  - Holes are trapped at interface SiO₂ - Si
  - Accumulated positive charge will reduce electric field near Si surface, reducing collection efficiency of charge carrier
  - N.B. charge carrier generated within 5nm at Si surface for VUV

- **Similar phenomena are known for UV photo diode**
  - Degradation happens only with much larger amount of light at room temp.
  - Degradation seems accelerated at low temp.

Highly Irradiated Samples

- Highly irradiated samples produced at irradiation facilities
- Tested in LXe

<table>
<thead>
<tr>
<th>Dose</th>
<th>Gamma [Gy]</th>
<th>Neutron [n_{1MeV/cm^2}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEG II (3yrs)</td>
<td>(1.4-4.1) \times 10^3</td>
<td>4.8 \times 10^9 - 2.0 \times 10^{12}</td>
</tr>
<tr>
<td></td>
<td>\sim 0.6</td>
<td>\sim 10^8</td>
</tr>
</tbody>
</table>

\[ \rightarrow \text{No effect on PDE!} \]
PDE for VUV Light

- PDE degradation was not observed for all irradiated samples.
- Overall PDE were lower than those of the previous measurements (14-20%) ← purity of LXe??
- Only PDE of #0660-0 was lower though other samples with the same dose level were not the case.
  - PDE of #0660-0 for visible light was similar to others. ← there might be a certain damage in the surface except for radiation damage.

※Errors include statistic errors and a systematic error of W value (10%)