Study on gain decrease of PMTs in MEG II gamma ray detector

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16pG22-10

JPS annual meeting @Nagoya Univ.
µ → eγ

- charged lepton flavor violation
  - practically forbidden in Standard Model by tiny neutrino mass
  - but many predictions by new physics are within experimental reach
    - eg. SUSY with GUT/Seesaw

- µ→eγ search
  - signal
    - both 52.8 MeV/c
    - back to back
    - same timing
  - dominant background: accidental

example of µ → eγ decay
MEG II Experiment

- MEG II is experiment to search for $\mu \rightarrow e\gamma$
- goal sensitivity: $6.0 \times 10^{-14}$ in 60 weeks
  - MEG I result:
    \[ Br(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13} \text{ (90\% C.L.)} \]
    (sensitivity: $5.3 \times 10^{-13}$)

- key concept:
  - high $\mu$ intensity: $7 \times 10^7 \mu/s$ @ PSI
  - high resolution detectors

- this talk is on $\gamma$ detector
LXe Detector

- LXe scintillator (VUV light ~175 nm)
- PMTs on $\gamma$ incident surface are replaced with MPPCs

- improve uniformity and granularity
  - energy resolution: 2\% \@ MEG I $\rightarrow$ 1\% \@ MEG II (expected)
  - position resolution: 5 mm \@ MEG I $\rightarrow$ 2.5 mm \@ MEG II (expected)

- need precise calibration of ~5000 photosensors
Photosensor Monitoring

- calibration sources
  - $^{241}$Am $\alpha$ ray source $\rightarrow$ absolute response for LXe scintillation light
  - blue LED $\rightarrow$ gain calculation by Poisson statistics, monitor relative variation by large photon statistics

- monitor during pilot run in 2018
  (ref: JPS2019a19pT14-6)
    - response decreased with muon beam
      $\rightarrow$ investigate in detail
      - PMT: this talk
      - MPPC: next 3 talks & 17aG22-7,8

![Graphs showing PMT and MPPC responses with data points and lines indicating trends over time. The graphs also show the number of incident VUV photons and their variation with date (1 month).]
Fast Gain Decrease
Calibration by Various Method

\[ \text{charge} = \text{LY} \times \text{QE} \times \text{CE} \times \text{G} \]

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<thead>
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<td>LY</td>
<td>Light Yield</td>
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<tr>
<td>QE</td>
<td>Quantum Efficiency</td>
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<td>Gain</td>
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LY : Light Yield  
no effect on LED light

QE: Quantum Efficiency  
dependent on wavelength

CE: Collection Efficiency

G : Gain  
calculated by LED Poisson statistics

- average of 200 PMTs in LXe detector
- decrease (\(~8\%\)) is consistent with each other within 1%
  \[ \Rightarrow \text{gain is main cause} \] of decrease
- possible cause:
  degradation of dynode material
Decrease Speed

- decrease speed gradually decreases
  - slower than exponential

![Graph showing average gain of 150 PMTs over irradiation days. The graph shows four lines with different slopes, indicating different decrease speeds: 4.4%/day, 1.5%/day, and 0.7%/day. The y-axis represents the average gain, and the x-axis represents irradiation days.]
Beam Rate Dependence of Decrease Speed

- compare decrease speed at different muon beam rate

- strong dependence on beam rate
- much faster decrease at MEG II nominal rate than expected from MEG I observation
- larger gain is available by applying large HV
- can operate at safe HV?
Fast Gain Decrease

HV Estimation

- estimate HV necessary after 3 years operation
- assumptions:
  - constant decrease rate: $G = G_0 e^{-\alpha t}$ (faster than observation)
  - HV dependence: $G = a(HV - HV_0)^k$
    - assume only $a$ becomes smaller
- result:
  - HV for most PMTs exceeds safety limit (1400 V)
    → need a way of making decrease slower
Half Gain Solution
Gain Dependence of Decrease Speed

- operation with half gain by lowering HV

- separate PMTs into 2 sets
- lowered HV of set A just after 3-day-operation
- **slower decrease** @lower gain
- most PMTs will be operated at safe HV with low-gain-operation

**Gain**
- set A: $1.6 \times 10^6 \rightarrow 0.8 \times 10^6$
- set B: $1.6 \times 10^6$

Normalized Charge for LED

**HV after 3 years**

- Mean: 992.8
- Std Dev: 162.8

- no beam for 3 days
- 0.9%/day
- 0.5%/day
Effect of Half Gain Operation

- smaller number of detected photons?
  - decrease of CE is only 5%
  - photon statistics does not largely contribute to resolutions (cf. 16pG22-13)

- worse S/N?
  - signal decrease can be compensated by doubling gain of readout electronics
  - no increase of noise observed → S/N does not change!
    (dominant noise seems to generate after amp of electronics)
Study on gain decrease of PMTs in MEG II gamma ray detector

Summary

- PMTs are used in $\gamma$ ray detector of MEG/MEG II experiment
- gain decrease correlated with muon beam
  - strong dependence on beam rate
  - so rapid that too large HV is necessary to compensate for decrease
- solution: half gain operation
  - smaller decrease at smaller gain $\rightarrow$ safe HV even after 3 years run
  - little effect on detector performance
    $\rightarrow$ to be checked by monochromatic 55 MeV $\gamma$ this year
Backup
PMT Principle

\[ G = \prod \alpha_i V_i^{k_i} \quad (i: \text{dynode}) \]
PMT Information

- R9288 & R9869
  - Size: 57 mm φ
  - Active area size: 45 mm φ
  - PMT length: 32 mm
  - Photo-cathode material: K-Cs-Sb
  - Dynode type: Metal channel → fast, small, robust for B-field

Aluminum strip → low temp.
Zener Diodes → large signal
MPPC Monitoring

- $\textit{charge} = N_{\text{photon}} \cdot PDE_\lambda \cdot \textit{gain} \cdot \textit{ECF}$
  - weak LED
    - Example of charge distribution
      - 0 p.e.
      - 1 p.e.
      - charge [$10^9 e$]
  - Strong LED: response for visible light
  - charge from scintillation by $\alpha$ from $^{241}\text{Am}$
  - current from scintillation by $\gamma$ from $\mu$

Charge follows “Poisson + correlated noise” distribution

\[ \text{gain} \cdot \text{ECF} = \frac{\text{mean}}{\mu} (\text{expected # of primary discharge}) \]

$\mu$ estimated from pedestal fraction:

\[ P(0 \text{ pe}) = e^{-\mu} \]

PDE: Photon Detection Efficiency (depend on wavelength)

gain: charge from 1 pixel

ECF: Excess Charge Factor

( = crosstalk + afterpulsing)
PMT Monitoring

- \( \text{charge} = N_{\text{photon}} \cdot \text{QE} \cdot \text{CE} \cdot \text{gain} \)

  - LED of different intensity

- Strong LED: response for visible light

- Charge from scintillation by \( \alpha \) from \(^{241}\text{Am}\)

- Current cannot be read out

\[
\text{gain} = \frac{\text{variance}}{\text{mean}}
\]

Charge follows Poisson distribution

\( \text{QE} \): Quantum Efficiency

\( \text{CE} \): Collection Efficiency

\( \text{gain} \): charge from 1 photoelectron

\( \text{variance} \) and \( \text{mean} \) depend on B-field.
Dose Estimation

- MPPC current for pulsed LED light (20 kHz)

signal size $\sim O(100 \text{ mV})$
Dose Estimation

- MPPC current for signals from muon beam
Irradiation of LED Light

- motivation: confirm that cause is dynode damage should be independent of wavelength

- setup
  - LED with pulse operation (1 MHz)
  - PMT with large gain \((5 \times 10^6)\)
  - MPPC for light monitor
Irradiation of LED Light

Result

- no decrease observed except for only a few % fluctuation
  - $> 5 \times 10^{16}$ photon/PMT/day for $>10$ days
  - $(2 \times 10^{13}$ photon/PMT/day for 6 days @LXe detector)
- possibly different in LXe temperature (165 K)