Study on Afterglow of LYSO scintillator crystal for MEG II Radiative Decay Counter

MEG II 実験放射崩壊同定用カウンターにおける
LYSOシンチレーターのアフターグローによる影響の評価

Ryoto Iwai (東大理)
on behalf of MEG II collaboration
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2. Feature of LYSO crystal
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1. Introduction

- The MEG experiment has been searching for charged lepton flavor violating decay $\mu \to e\gamma$

This is predicted to occur at a sizable rate by many models beyond the Standard Model

- The most dominant background (BG) in the experiment

- It will be upgraded as MEG II experiment with higher $\mu$ beam intensity ($7 \times 10^7 \mu/s$) with higher BG rate
1. Introduction

- Radiative Decay Counter (RDC) will be newly installed to identify the accidental BG.

- High $e^+$ hit rate for each counter (200~600kHz)

- Downstream detector was constructed and tested in 2015 (detail in next talk)
  - Operation test with $\mu$ beam in June, 2016

- Upstream detector will be constructed after R&D
  - Scintillation fibre detector
  - Study of the influence on $\mu$ beam is ongoing

<table>
<thead>
<tr>
<th>MEG II sensitivity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o RDC</td>
<td>$5.0 \times 10^{-14}$</td>
</tr>
<tr>
<td>w/ downstream</td>
<td>$4.3 \times 10^{-14}$</td>
</tr>
<tr>
<td>w/ downstream + upstream*</td>
<td>$3.9 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

$*$assuming detection efficiency ~90%
1. Introduction

- Downstream detector consists of timing counter & calorimeter

**Timing counter part**
- Measuring timing of low momentum $e^+$
- 12 plastic scintillator bars readout with MPPCs
- ~90psec resolution was obtained

**Calorimeter part**
- Measuring energy to distinguish RMD from Michel Decay
- 76 LYSO crystals readout with MPPCs
- ~6% resolution was obtained (for 1MeV)

- We observed afterglow of LYSO crystal during the mass test
2. Feature of LYSO crystal

- LYSO (Lutetium-Yttrium Oxyorthosilicate) is an inorganic scintillator.
- It has advantages of a high light yield and fast signal.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>$2\times2\times2\text{cm}^3$</td>
</tr>
<tr>
<td>Density</td>
<td>$7.4\text{g/cm}^3$</td>
</tr>
<tr>
<td>Decay constant</td>
<td>42ns</td>
</tr>
<tr>
<td>Emission peak</td>
<td>420nm</td>
</tr>
<tr>
<td>Light yield</td>
<td>$3\times10^5\text{ph/MeV}$</td>
</tr>
</tbody>
</table>

- LYSO is also known to have afterglow (phosphorescence):
  - Some excited electrons are trapped in lattice defect and emit late scintillation light.
  - Induce readout noise after irradiation ($\gamma$-ray, neutron irradiation in previous study).
- We studied $\beta$-ray induced afterglow by monitoring anode current.
- We measured several crystals and checked correlation with room light afterglow.
3. Afterglow study with room light

- We built a single channel setup to monitor current of MPPC
  → voltage & temperature was also monitored

- We observed afterglow with room light
  (presented at last JPS meeting)

Current readout value with picoammeter after exposed room light for 24h

Temperature is constant (30°C)

Serial number of LYSO

Current (µA)

Serial number of LYSO

LYSO serial #54
decreasing current after exposed light
4. Study with Sr90 source

• We also observed afterglow induced by β-ray irradiation (presented at last JPS meeting)

• We observed current increasing exponentially for first few hours

• The effect on energy resolution was found to be negligible

• Why does the current rise exponentially due to afterglow?

\[ \text{emitted } N_{\text{photon}} \text{ was calculated with random number following exponential dist.} \]

\[ \text{→ Trapped electrons will be released with certain probability in } \Delta t \]

\[ \text{→ Emitting time will follow geometric dist. (exponential dist. for } \Delta t \to 0) \]
4. Study with Sr90 source

- We also observed afterglow induced by β-ray irradiation (presented at last JPS meeting)

- Current with Sr90 irradiation (LYSO #45)

- Why does the current rise exponentially due to afterglow?

  - Trapped electrons will be released with certain probability in $\Delta t$
  - Emitting time will follow a geometric distribution (exponential distribution for $\Delta t \to 0$)

emitted $N_{\text{photon}}$ was calculated with random number following exponential distribution.

$N_{\text{photon}}$ was calculated with random number following exponential distribution.

$\rightarrow$ Trapped electrons will be released with certain probability in $\Delta t$

$\rightarrow$ Emitting time will follow a geometric distribution (exponential distribution for $\Delta t \to 0$)

In this talk, we will show the result about initial increasing current.
4. Study with Sr90 source

- For further study, we checked reproducibility of afterglow with Sr90 (3.7MBq)

1. Irradiation (current 7~9μA)  
2. Shielding (current 0.5~2.5μA)  
3. Fitting function

\[
I = C_1 \pm e^{-\frac{t-C_2}{\tau}}
\]

where \( \Delta I_{\text{max}} = e^{\frac{C_2}{\tau}} \)

\[
\Delta I_{\text{max}} = 1.50\mu \text{A} \\
\tau = 1.77
\]

\[
\Delta I_{\text{max}} = -1.49\mu \text{A} \\
\tau = 1.73
\]
4. Study with Sr90 source

- From past study, room light afterglow are known to have individual difference

- We additionally measured 5 crystals with room light → After exposed room light 24h~, current was measured with picoammeter

- These 5 crystals were measured with Sr90 (37MBq) and checked correlation → Hit rate was also measured after current monitor (~400kHz)
4. Study with Sr90 source

- Result of the current (+1 crystal was measured additionally)

**#45**  $\Delta I_{\text{max}} = 4.25 \mu A$

**#1**  $\Delta I_{\text{max}} = 0.34 \mu A$

**#35**  $\Delta I_{\text{max}} = 0.63 \mu A$

**#62**  $\Delta I_{\text{max}} = 0.37 \mu A$

**#8**  $\Delta I_{\text{max}} = 1.73 \mu A$

**#26**  $\Delta I_{\text{max}} = 3.74 \mu A$
4. Study with Sr90 source

- Correlation was checked (grey plot shows additional measurement)

- $\Delta I_{\text{max}}$ has a correlation with the amount of increased current with room light afterglow

- This result can be useful to optimize the placement of crystals in the detector
4. Study with Sr90 source

- Different strength Sr90 was applied to same crystal (#45)
- $\Delta I_{\text{max}}$ & $\tau$ are expected to be proportional to hit rate
- Hit rate was measured with discriminator & scaler

- $\Delta I_{\text{max}}$ was largely changed with different hit rate
5. Summary of afterglow study

We had already observed at the last JPS meeting...
- Large anode current after exposed to room light in several crystals
- Slowly increasing current during β-ray irradiation
  (the influence on detector operation was estimated small)

We newly observed...
- Current increasing (decreasing) exponentially during (after) β-ray irradiation
- Each crystals have unique $\Delta I_{\text{max}}$ & $\tau$ for both increasing & decreasing
- $\Delta I_{\text{max}}$ has a correlation with afterglow induced by room light
- $\Delta I_{\text{max}}$ was largely changed with different hit rate

We will do next...
- We will investigate about slowly increasing current
  (also measure scintillation properties)
Back up
4. Study with Sr90 source

<table>
<thead>
<tr>
<th>LYSO serial</th>
<th>meas. order</th>
<th>$\Delta I_{\text{max}}$ (µA)</th>
<th>$\tau$ (hours)</th>
<th>hit rate (kHz)</th>
<th>light yield (a.u.)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>#45</td>
<td>1</td>
<td>4.25</td>
<td>1.84</td>
<td>372</td>
<td>8.98</td>
</tr>
<tr>
<td>#1</td>
<td>2</td>
<td>0.34</td>
<td>1.54</td>
<td>390</td>
<td>7.47</td>
</tr>
<tr>
<td>#35</td>
<td>3</td>
<td>0.63</td>
<td>1.33</td>
<td>408</td>
<td>9.70</td>
</tr>
<tr>
<td>#62</td>
<td>4</td>
<td>0.37</td>
<td>1.70</td>
<td>367</td>
<td>6.32</td>
</tr>
<tr>
<td>#8</td>
<td>5</td>
<td>1.73</td>
<td>0.67</td>
<td>433</td>
<td>9.02</td>
</tr>
<tr>
<td>#26</td>
<td>6</td>
<td>3.74</td>
<td>1.24</td>
<td>343</td>
<td>9.79</td>
</tr>
</tbody>
</table>

* light yield was measured by using 1.17MeV peak of Co60
4. Study with Sr90 source

**Graph #8**

* light yield was measured by using 1.17MeV peak of Co60
Study with Y88 source

\[ \Delta I_{\text{max}} = 0.12 \mu A \quad \tau = 3.25 \]

\[ \chi^2 / \text{ndf} = 946.4 / 447 \]

\[ p_0 = 2.052 \pm 0.001 \]

\[ p_1 = 0.5775 \pm 0.0301 \]

\[ p_2 = -3.609 \pm 0.206 \]
372kHz

\[ \Delta I_{\text{max}} = 4.25 \mu A \]
\[ \tau = 1.84 \]

\[ \chi^2 / \text{ndf} = 956.2 / 477 \]
\[ p_0 = 32.71 \pm 0.00 \]
\[ p_1 = 0.5434 \pm 0.0025 \]
\[ p_2 = 2.661 \pm 0.012 \]
Pics of Calorimeter part

LYSO crystals + main frame

back plane + PCB

MPPC is fixed with spring
4. Study with Sr90 source

incident photons = 5000 per sec

incident photons = 10000 per sec

incident photons = 15000 per sec
Reproducibility of $\Delta I_{\text{max}}$ & $\tau$ in #45

1st measurement

$\Delta I_{\text{max}} = 4.14 \mu A$
$\tau = 1.90$

2nd measurement

$\Delta I_{\text{max}} = 4.25 \mu A$
$\tau = 1.84$

| $\chi^2$ / ndf | 956.6 / 477 |
| p0 | 34.54 ± 0.00 |
| p1 | 0.5252 ± 0.0027 |
| p2 | 2.704 ± 0.013 |

| $\chi^2$ / ndf | 956.2 / 477 |
| p0 | 32.71 ± 0.00 |
| p1 | 0.5434 ± 0.0025 |
| p2 | 2.661 ± 0.012 |
Specifications

Cerium-doped lutetium yttrium oxyorthosilicate crystal ((Lu,Y)2SiO5:Ce, namely LYSO:Ce), is colorless and transparent, characterized by monoclinic structure. LYSO not only has excellent scintillation properties such as high light output, short decay time, high density and radiation hardness; but also has its emission peak wavelength 420 nm located in the sensitive region of PMT, and hence the emission can be effectively detected; besides, it has stable physical and chemical properties and hence is convenient for application. Therefore, LYSO is an excellent scintillation crystal.

LYSO can be widely applied in the fields of nuclear medicine, high-energy physics and so on. It benefits detectors for obtaining high time resolution, spatial resolution and miniaturization.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g.cm⁻³)</td>
<td>7.4</td>
</tr>
<tr>
<td>Radiation length (cm)</td>
<td>1.14</td>
</tr>
<tr>
<td>Decay constant (ns)</td>
<td>42</td>
</tr>
<tr>
<td>Emission peak (nm)</td>
<td>420</td>
</tr>
<tr>
<td>Light yield (P.h./MeV)</td>
<td>30000</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>2150</td>
</tr>
<tr>
<td>Hardness (Mho)</td>
<td>5.8</td>
</tr>
<tr>
<td>refractive Index (@405 nm)</td>
<td>1.83</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>none</td>
</tr>
<tr>
<td>Cleavage</td>
<td>none</td>
</tr>
</tbody>
</table>
Energy resolution calculation

- How much resolution gets worse if p.e. from AG are increased
- 2 assumptions
  1. Single waveform contains $N_{\text{all}}$ photoelectons
  
  $N_{\text{all}} = N_{\text{sig}} + N_{\text{AG}}$

  2. $N_{\text{AG}}$ shifts mean value in charge distribution

Resolution = \[
\frac{\sigma_{\text{all}}}{N_{\text{all}} - N_{\text{AG}}}
\]

= \[
\frac{\sigma_{\text{all}}}{N_{\text{sig}}}
\]
Energy resolution calculation

Resolution = $\frac{\sigma_{all}}{N_{sig}}$

= $\sqrt{\frac{N_{sig} + N_{AG}}{N_{sig}}}$

= $\frac{1}{\sqrt{N_{sig}}} \sqrt{1 + \frac{N_{AG}}{N_{sig}}}$

= $\frac{1}{\sqrt{N_{sig}}} + \text{terms with } N_{AG}$

If it follows a Poisson distribution…

$N_{all} = N_{sig} + N_{AG}$

$\sigma_{all}^2 = \sigma_{sig}^2 + \sigma_{AG}^2$

$\sigma_{sig} = \sqrt{N_{sig}} \quad \sigma_{AG} = \sqrt{N_{AG}}$

$\sigma_{all} = \sqrt{N_{sig} + N_{AG}}$

We can estimate additional terms from $N_{sig}$ & $N_{AG}$
Energy resolution calculation

- Consider waveform of 1.17MeV Co60 peak

\[ N_{AG} = \frac{\text{Current}[c/s] \times \text{Wavelength}[s]}{\text{Gain of MPPC} \times e[c]} \]

\[ N_{\text{sig}} = N_{\text{all}} - N_{AG} \]

\[ = \frac{\text{Charge at 1MeV}}{\text{Charge at 1p.e.}} - N_{AG} \]

- If current is increased 50μA...

\[ N_{AG} \approx 401 \]

\[ N_{\text{sig}} \approx 3491 - 401 \]

\[ = 3090 \]

Resolution gets worse \( \sim 0.2\% \)
Status of RDC

**Downstream detector**

- R&D, prototype beam test (~2015)
- Construction and lab test (December, 2015)
  → Next talk (S. Nakaura, 19aAH-11)
- Operation test with $\mu$ beam (June, 2016)
  → We will take coincidence with $\gamma$ by using BGO detector in stead of LXe detector
- MEG II Engineering run (in 2016)

**Upstream detector**

- R&D, prototype beam test (~2015)
- Monte Carlo study (~March, 2016)
- Construction and operation test (in 2016)
RDC upstream detector

- R&D is still ongoing
- The influence on $\mu$ beam spot on the target was studied with a mock-up
  $\rightarrow \sigma_x \cdot \sigma_y$ was changed factor of 1.16

Scintillation fibre

- Measuring timing of low momentum $e^+$
- 784 scintillation fibers (265-270$\mu$m thickness) are used
- MPPC will be used for reading out

The influence on $\mu$ beam was studied with Monte Carlo

<table>
<thead>
<tr>
<th>target size</th>
<th>$\mu$ stopping efficiency</th>
<th>long track efficiency</th>
<th>TC hitting efficiency</th>
<th>total efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>-3.13%</td>
<td>-0.61%</td>
<td>-0.21%</td>
<td>-3.90%</td>
</tr>
<tr>
<td>bigger</td>
<td>-3.00%</td>
<td>-0.74%</td>
<td>-0.25%</td>
<td>-3.81%</td>
</tr>
</tbody>
</table>
paper of afterglow
Gamma Ray Induced Radiation Damage in PWO and LSO/LYSO Crystals

Rihua Mao, Member, IEEE, Liyuan Zhang, Member, IEEE, and Ren-Yuan Zhu, Senior Member, IEEE
sample were wrapped with the Tyvek paper. A collimated $^{137}$Cs source was used to excite the PWO sample. To reduce the effect of the intrinsic natural radioactivity, a collimated $^{22}$Na source was used to excite the LSO/LYSO samples with a coincidence trigger provided by a BaF$_2$ crystal [2]. The $\gamma$-size of the LSO/LYSO samples. Also shown in this figure is the electronic noise (E-Noice), which is measured without crystals. While the $\gamma$-ray induced phosphorescence (afterglow) is found approaching the E-Noice, so is negligible (at $10^{-5}$ level) in the PWO and BGO samples, it is between $10^{-3}$ and $10^{-4}$ in the LSO and LYSO samples. The LYSO sample from

![Graph showing normalized anode current as a function of time during and after $\gamma$-ray irradiations for the PWO, LSO/LYSO and BGO samples.](image)
Effects of Neutron Irradiations in Various Crystal Samples of Large Size for Future Crystal Calorimeter

Liyuan Zhang, Member, IEEE, Rihua Mao, Member, IEEE, and Ren-Yuan Zhu, Senior Member, IEEE
4 MeV neutrons from one $^{241}$Am-Be source and 2.5 MeV neutrons from two $^{252}$Cf sources are used for irradiation source. Neutron induced radiation damage effects in these sources (red dots), for six samples. Since the LYSO samples have a strong phosphorescence if exposed to light they have to be kept in dark for more than 24 h before starting the test as shown in the middle top plot for the SIPAT-L2 sample. The reading of the neutron induced photo-currents during irradiations was set to be around hundred nA by adjusting the PMT bias to avoid possible PMT gain saturation. The photocurrent was found to be stable during the one week irradiations by the $^{241}$Am-Be source, indicating no cumulative effect from neutrons. Also shown in the figure is the time constant for the cool-down of the neutron induced phosphorescence. It is about 2, 10 and 35 hours for BGO, LYSO and PWO respectively. The

Fig. 5. The anode photo-current measured during irradiations by the $^{241}$Am-Be (blue dots) and $^{252}$Cf sources (red dots) is shown as a function of time for BGO and CeF$_3$ (Left), two LYSO (Middle) and two PWO (Right) samples. Also shown is the exponential fit of the cool-down time of the neutron-induced phosphorescence.
Large Size LYSO Crystals for Future High Energy Physics Experiments

Jianming Chen, Member, IEEE, Liyuan Zhang, Member, IEEE, and Ren-Yuan Zhu, Senior Member, IEEE
The radiation induced phosphorescence spectra of the CPI and Saint-Gobain long LYSO samples were continuously measured for more than 48 h after 22 h irradiations at 9000 rad/h. No variation of the phosphorescence spectra were observed for both samples. The amplitude of phosphorescence, normalized to 1 h after the end of the irradiation, were fit to an exponential function

\[ A = A_0 + A_1 e^{-t/\tau}. \] (5)

Fig. 18 shows the fit result. The decay time constants of the radiation induced phosphorescence were determined to be 2.5 h and 3.6 h respectively for the CPI and the Saint-Gobain samples. The Saint-Gobain sample is also noticed to have a slightly larger residual phosphorescence. To evaluate the radiation in-

![Graph showing phosphorescence spectra](image)

**Fig. 18.** Amplitude of phosphorescence is shown as a function of time after 22 h irradiation at 9000 rad/h for the (top) CPI and (bottom) Saint-Gobain long LYSO samples.