Development of a new inorganic crystal GAGG for the calorimeter capable of the separation between neutrons and gammas

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• Introduction of GAGG crystals

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• Summary
Motivation of the calorimeter capable of the separation between neutrons and gammas

- KOTO experiment
  - Search for $K_L \rightarrow \pi^0 \nu \nu$
    - Breaks CP symmetry directly.
      Suppressed in the standard model.
      -> Sensitive to New Physics
  - Signature for $K_L \rightarrow \pi^0 \nu \nu$
    「2 $\gamma$ + nothing」
  - Neutron is a main background source
    - The separation between neutrons and gammas is important
  - Neutron energy $\sim 1$GeV.
**GAGG(Gd$_3$Al$_2$Ga$_3$O$_{12}$(Ce)) Crystal**

- High density
- High light yield (as high as NaI)
- Fast response

<table>
<thead>
<tr>
<th></th>
<th>GAGG(Ce)</th>
<th>Mg-doped GAGG(Ce)</th>
<th>Undoped CsI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density(g/cm$^3$)</strong></td>
<td>6.67</td>
<td>6.67</td>
<td>3.67</td>
</tr>
<tr>
<td><strong>Light yield</strong></td>
<td>127</td>
<td>100</td>
<td>1.1</td>
</tr>
<tr>
<td>(NaI(Tl)=100)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Decay time(ns)</strong></td>
<td>90</td>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td><strong>Peak emission(mm)</strong></td>
<td>520</td>
<td>520</td>
<td>310</td>
</tr>
</tbody>
</table>
Method of the separation between neutrons and gammas
(Separation by pulse shape)

The response of liquid scintillators depends on incident particles


→Check whether the response of GAGG is different between neutrons and gammas
Method of the separation between neutrons and gammas (Separation by interaction depth)

- Gammas: Radiation length
- Neutron: Interaction length

Make the difference of interaction depth in the crystal

- Glue two crystals with a different amount of doped materials
- Measure interaction positions by the observed pulse shape
Dependence of light yield and decay constant on doped material

- Measured with a small crystal

Profile

Relative light yield

~1 mm thickness

![Graph showing the profile and relative light yield vs. fraction of Mg]
Positron/neutron beam tests with a prototype module

- Attach a 2inch-PMT to this side

Mg 1%
Diameter: 51.3mm
Length: 100.2mm
(6.4X0)

Mg 0%
Diameter: 47.2mm
Length: 99.9mm
(6.3X0)

After shielding the crystals and attaching the PMT

Glued two crystals with optical cement (BC-600)
Positron beam test

- ELPH @ Tohoku University
  - 200-800MeV positron
  - Beam size@GAGG crystal
    - $\sim 1 \times 1 \text{cm}^2$
  - Recorded waveforms of the GAGG crystal with a 500 MHz FADC
  - Irradiated the positron beam to the GAGG crystal in parallel or vertical

3x3 cm$^2$ scinti.  
Fast response PMTs  
1x1 cm$^2$ scinti.  
GAGG crystal $\phi \sim 50\text{mm}$  
L=200mm
Response to longitudinal direction

- Light Yield of GAGG Crystals
  - (Mg 0%) \sim (Mg 1%) \times 2
- Deviation of light yield is within 10%.
  -> Due to loss at the connection surface.
Response to longitudinal direction

- Waveforms
- Depend on incident beam positions
- Can be separated by Peak/Integral

460MeV e+ beam

Mg 0%

Mg 1%

PMT

0mm

40mm

100mm

140mm

200mm

40mm

140mm

Arbitrary unit

峰/积分

(sample /2ns)

Arbitrary unit

(sample /2ns)
Response around connection surface of two crystals

- The waveforms from two crystals seem to be mixed.
Neutron beam test

- RCNP @ Osaka University

- Proton beam: Energy 250MeV, Mean current 85nA
  RF cycle: 68ns, Chopping: 1/9

- $^7$Li(p,n)$^7$Be: Quasi mono-energetic neutron
  250MeV proton -> 250MeV neutron

- Data taking
  - Self-triggered by GAGG
  - Recorded waveforms by a 500MHz FADC
Neutron identification

- Use time difference between RF signal ($T_{RF}$) and GAGG signal ($T_{GAGG}$)
  - $|T_{RF} - T_{GAGG} - 26\text{ns}| < 5\text{ns}$

![Graph showing contribution from next RF timing and gammas from the target]
Waveforms for different particles

- Mg 0%
  - Neutrons have wider width
  - No difference between e⁺/μ
- Mg 1%
  - No difference
Peak/Integral for neutron events

250MeV neutron \[ \rightarrow \] Mg 0%  Mg 1%  PMT

**Graph:**
- **Y-axis:** Arbitrary unit
- **X-axis:** Peak/Integral
- **Data points:**
  - GAGG Mg 0%
  - GAGG Mg 1%
  - Interact in both crystals
Evaluation of neutron/gamma separation

- Mg 0%
  - Waveforms are different between neutrons and $e^+$
- Select events inside the blue region
  - Achieve 94% efficiency for $e^+$ while 95% of neutrons can be rejected.
Summary

• GAGG crystals have high density and fast response.
  -> suitable for calorimeters in high energy physics experiments

• Evaluated the capability of separation between gammas and neutrons with the prototype module consisting of two GAGG crystals with a different amount of doped materials
  • Found response of GAGG crystals are different between gammas and neutrons.
  • Can reject 95% of neutrons while keeping 95% efficiency for positrons.
• Backup
Incident in Longitudinal

\[ z \text{ (mm)} = 200 \quad 100 \quad 0 \]

Position beam
200 - 800 MeV

No Mg
Mg (1%)
PMT

200 MeV

Black : Real
Red : M.C.

800 MeV

Calibration was done by peak position of 200 MeV
Calibration was determined by 200 MeV

Peak position is reproduced by M.C.

Linearity

Calibration was determined by 200 MeV

Peak position is reproduced by M.C.