The upgrade of the KOTO CsI calorimeter for the separation of $n$ and $\gamma$

Nobuhiro Shimizu for the KOTO collaboration

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Introduction
KOTO experiment

• $K_L \to \pi^0 \nu \bar{\nu}$

Very rare decay:
$\mathcal{B}_{SM}(K_L \to \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$

• Detector

Signal: $2\gamma + $ nothing
Two electromagnetic showers in CsI and no signal in the hermetic veto counters

Key: avoid missing photons and exclude neutron-induced BG
CsI calorimeter of the KOTO detector

- **CsI crystal**
  - Undoped CsI (\(\lambda \sim 300\) nm)
  - #crystal = 2716
  - 2240 small (25 \(\times\) 25 mm\(^2\))
  - 476 large (50 \(\times\) 50 mm\(^2\))

- **Excellent energy resolution**
  - \(\sigma_E/E = 0.99\% \oplus 1.74\%/\sqrt{E[GeV]}\)

- **PMT signals are digitized by ADC**
  - 14 bit 125 MHz sampling with Gaussian filter
  - 512 ns timing window (64 samples)
  - Timing resolution \(\sigma_t \sim 1\) ns
Neutron background

To achieve SM sensitivity, we need to suppress neutrons by a factor of ten.
Idea of the CsI calorimeter upgrade

Previous

Attach MPPCs

Measure the depth with the time difference $\Delta T \equiv T_{MPPC} - T_{PMT}$

$\Rightarrow$ Small $\Delta T$ implies $\gamma$
Readout
New front-end readout

- MPPC readout
  
  # of MPPCs: \textbf{4080} (>\#PMT=\#CsI)

  \textit{To reduce \# of channels..}
  
  4 MPPCs are connected

- Bias connection

  \textbf{“Hybrid” bias connection}
  
  - adopted by MEG II upgrade
  - AC line: series, to read out signals
  - DC line: parallel, to apply bias voltage
Development of front-end: amplifier

32 hybrids are connected to one board

4 MPPCs are connected $\times \frac{1}{4}$

4 readout is summed $\times \frac{1}{4}$

$\Rightarrow$ Manageable number of channels
Segmentation

Read 10 cm x 10 cm region as a single channel

\sim \text{typical size of EM shower}

Small crystals

Large crystals

Front-end electronics
Installation of MPPCs
MPPC on the CsI surface

Two problems to be addressed

① Concave shape of MPPC

Quartz plate to make sure the flatness and transparency in advance

② Bubbles appear at low temperature

$T \sim 5 \degree C$

Keep positive pressure inside the glue

Wait for curing strong glue

Quartz plate to make sure the flatness and transparency in advance

$\text{CsI}$

UV-transparent Glue

Quartz

silicone

MPPC

weight

strong glue
MPPC installation

Frames to support gluing jigs
MPPC instrumentation

- Glue MPPCs on two rows in a day
- Start from 1st Oct. and 45 days to finish all
- Installation finished as scheduled

Progress

#MPPC

0 50 100 200 250 300 350 400

0 10 20 30 40

Days

1st Oct. 1st Nov. 15th Nov.
New outer wear of the calorimeter
2019 run
Data correction in 2019 runs

In spite of the limited time schedule, we could collect physics data with new detectors!
Increase of dark current of MPPC due to irradiation → 20 times larger than what we had expected

Separately evaluated by another beam test at Kobe Tandem facility
Even with >50 times the irradiation in 2019, the timing resolution will be within our specification.
Analysis
Control sample

- Control of sample of $\gamma$
  - $K_L \rightarrow 3\pi^0$ decay
  - Clean and abundant control sample of $\gamma$

- Control sample of neutron

Insert Al plate in the upstream of detector. Scattered neutrons well emulate the BG of physics data.
Use the larger $\Delta T$ out of two clusters ($\max\Delta T$)

$K_L \to 3\pi^0$ MC well reproduces the distribution of data
Emulated distribution of $K_L \rightarrow \pi^0 \nu \bar{\nu}$

- The spectra of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is harder than $K_L \rightarrow 3\pi^0$ decay.
- Weight based on $w(E) = \frac{PDF(\pi^0 \nu \bar{\nu})(E)}{PDF(3\pi^0)(E)}$

Retaining 90% of $\gamma$ from $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay, neutron contribution can be suppressed down to 1/45! Achieve much better performance than the goal of design 1/10.
KOTO collaboration aims to search for New Physics via very rare decay $K_L \to \pi^0 \nu \bar{\nu}$, $B_{SM} = (3.0 \pm 0.3) \times 10^{-11}$.

In the last autumn, we attached >4000 MPPCs on the front surface of CsI crystal to improve $\gamma/n$ separation power:

- In 2019 run, we successfully collected physics data and confirmed
  - irradiation of MPPCs was acceptable for future data collection
  - performance of the neutron rejection was to be $1/45$ (for 90% $\varepsilon$ of signal), which was much better than our goal of design

Detector paper is now under preparation
That’s all

Thank you!
Degradation of neutron rejection

Neutron rejection vs additional degradation of timing resolution

Efficiency of neutrons with retaining 90% efficiency of $\gamma$

Smearing $\sigma$ (ns)
Correlation b.t.w. CSDL vs $\Delta T$

Let us separate regions into “front” and “rear” region and evaluate the reduction by applying CSDL value > 0.9.

We cannot see strong degradation of the performance of neutron rejection by CSDL.

(Rather, E dependence can be observed.)

Correlation does not look large.

Q. Does the CSD see the depth of clusters?
Let us separate regions into "front" and "rear" region and evaluate the reduction by applying PSLH value > 0.1. (pulse shape template is run74,75)

For high energy cluster, we can observe small correlation between PSLH and $\Delta T$.

Nevertheless, the degradation of performance is by a factor of 1.5.

Correlation does not look serious.
Effect of the irradiation

- Dark current
  - Increases $\times 100$ for
    $\sim 1 \times 10^9$ 1MeV-$n$/cm$^2$ (3-years operation)
  - Prepare irradiated sample of MPPCs

- Instability of bias voltage

Series connection causes instability of bias for the series connection.

$\Rightarrow$ Solved by adopting the Hybrid connection
Performance tests ($\gamma/n$ separation)

- Beam test at RCNP-Osaka cyclotron
  - $\gamma/n$ beam from Li target
    - $\gamma$: continuous beam up to 392 MeV
    - $n$: 392 MeV

$\gamma$: continuous beam up to 392 MeV

$n$: 392 MeV

Distribution

$$\Delta t \equiv T_{\text{MPPC}} - T_{\text{PMT}}$$

Retain 90% of $\gamma$ while suppressing $n$ to 34%
Performance tests ($\sigma_{\Delta t}$)

- Beam test at the ELPH (Tohoku, Japan) electron synchrotron
  - evaluate $\sigma_{\Delta t}$ (as a func. of $E$)
    - Monochromatic 200, 400, 600, 800 MeV $e^+$ beams
  - Used setup as realistic as possible
  - Confirmed MPPC functionality after dose
    - Irradiated MPPCs were used

- Irradiated MPPCs worked enough
- Readout worked well

![Graph showing $\sigma_{\Delta t}$ vs. $E_{beam}$]

![Diagram of beam test setup with regions L0 to L4, S0 to S3, and positrons (200-800 MeV)]
\( K \to \pi \nu \bar{\nu} \) decay

- Suppressed by FCNC in the SM
- Small QCD uncertainty
  - useful prove to the New Physics
- Two compatible processes
  - \( K^+ \to \pi^+ \nu \bar{\nu} : \mathcal{A} \propto |V_{td}| \)
  - \( K_L \to \pi^0 \nu \bar{\nu} : \mathcal{A} \propto \text{Im} V_{td} \)

**EXP**

\[ \mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8} \ (90\% \ C.L.) \] E391a

\[ \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-9} \] E949

**SM prediction**

\[ \mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11} \]

\[ \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11} \]
Rejection of neutron BG

**Halo-neutron BG**

Result of 4 days run: \( \mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8} \) (90% C.L.)

<table>
<thead>
<tr>
<th>Background source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_L \to 2\pi^0 )</td>
<td>0.047 ± 0.033</td>
</tr>
<tr>
<td>( K_L \to \pi^+\pi^-\pi^0 )</td>
<td>0.002 ± 0.002</td>
</tr>
<tr>
<td>( K_L \to 2\gamma )</td>
<td>0.030 ± 0.018</td>
</tr>
<tr>
<td>Pileup of accidental hits</td>
<td>0.014 ± 0.014</td>
</tr>
<tr>
<td>Other ( K_L ) background</td>
<td>0.010 ± 0.005</td>
</tr>
<tr>
<td>Halo neutrons hitting NCC</td>
<td>0.056 ± 0.056</td>
</tr>
<tr>
<td><strong>Halo neutrons hitting the calorimeter</strong></td>
<td>0.18 ± 0.15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.34 ± 0.16</td>
</tr>
</tbody>
</table>

*The largest contribution from BG*

- We need 3 more magnitudes of suppression
  - two-dimensional shower envelope \( \rightarrow 1/10 \) ✓ done
  - Pulse shape likelihood \( \rightarrow 1/10 \) ✓ done

measure shower development (in \( z \))

in the calorimeter \( \rightarrow \mathcal{O}(1/10) \)
Performance tests ($\gamma/n$ separation)

MC evaluation of performance for halo neutron events, based on the result of beam test

- Taking into account...

1. Correlation of two cluster position:
   - the second cluster is deeper

   The larger one $\rightarrow \Delta t_{max}$
   The smaller one $\rightarrow \Delta t_{min}$

2. Other neutron cuts

   $\rightarrow$ suppresses halo neutron BG to 10%
   while retaining 90% efficiency of two $\gamma$ signal events!
Quality assurance of MPPCs

- Quartz gluing
- Soldering
- temperature test
- I/V inspection
- LED test

Process 80 MPPCs/day

Inspect all of MPPCs (#~4000) before installation
→ Start gluing on CsI in this summer

I/V curves
#MPPC~500

Summed MPPCs

Individual test

MPPCs
DC dark current is continuously monitored to confirm the functionality and level of radiation damage.

Operation current increases by a factor of 100 in three snowmass year: $I_{op} = 0.5\mu A \rightarrow 50\mu A$
Development of front-end

- **MPPC readout**
  - Two types of crystals
  - 4 MPPCs are simultaneously read out

- **Bias connection**
  - **Series**
    - Small time constant (~200ns)
    - High bias voltage (220V)
    - Unstable individual operation
  - **Parallel**
    - Large time constant (~0.5us)
    - Low bias voltage (55V)
    - Stable breakdown voltage toward irradiation

"Hybrid"-connection
- Adopted by Meg2 upgrade
- AC line: series
- DC line: parallel
- Have both pros
Fabrication of MPPCs

1. Insert MPPC on jig
2. Drop glue
3. Drop glue on quartz
4. Wait for cure keeping the quartz floated
5. Put MPPCs into oven and wait 24 h (keeping 45 deg)
6. Dispense epoxy glue (araldite 2011)
7. Apply weight
8. Wait 24 h for cure
I/V inspection of MPPCs

I/V inspection front end

OPAMP
→ FET input (high impedance)
Gain 100

Basic design
• 16ch are chosen by MUX
• DC voltage is buffered by voltage follower after the MUX