New results of $K_L \rightarrow \pi^0\nu\bar{\nu}$ from J-PARC KOTO

Kota Nakagiri (Kyoto Univ.)
on behalf of the KOTO collaboration
**K_L → π^0νν Decay**

- **direct CPV**
- highly suppressed in the SM: \( Br = 3 \times 10^{-11} \)
- theoretically clean: \( \sim 2\% \)
  - good probe for new physics that breaks CP symmetry

**direct limit**: \( 2.6 \times 10^{-8} \) (90\% C.L.)

**indirect limit** (Grossman-Nir bound)
\[
Br(K_L) < 4.4 \times Br(K^+) = 1.5 \times 10^{-9}
\]

**a model w/ heavy Z' (50 TeV)**
\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

**K system**: \( \lambda^5 \ll B_d \) system: \( \lambda^3 \)

**1σ from exp.**

**SM**
**SM + NP**

**NP ?**

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M.Tanimoto, K.Yamamoto, PTEP2016,12,123B02
KOTO Experiment @ J-PARC

K⁰ at TOkai

Tokai village

Japan Proton Accelerator Research Complex = J-PARC

30GeV Proton Beam

KL beam

Au target

KOTO

J-PARC = Japan Proton Accelerator Research Complex
**Experimental Method**

: Signal detection

\[ K_L \rightarrow \pi^0 + \nu \bar{\nu} \]

\[ \pi^0 \rightarrow 2\gamma \text{ on CSI calorimeter} \]

Csl Calorimeter (CSI)
Experimental Method

\[ K_L \rightarrow \pi^0 \nu \bar{\nu} \]

\[ \pi^0 \rightarrow 2\gamma \] on CSI calorimeter

missing : hermetic veto around the decay volume

Veto counters

CSi Calorimeter (CSI)

\[ (\pi^0) \rightarrow \gamma \gamma \]
Experimental Method

: Background rejection

\[ K_L \rightarrow \pi^0 \pi^0 \rightarrow \gamma \gamma \gamma \gamma \]

\[ K_L \rightarrow 2\pi^0 \text{ BG} \]

CSI Calorimeter

Veto counters

\[ K_L \rightarrow (2\pi^0) \]

\[ R \sim 1\text{m} \]
Experimental Method

: $\pi^0$ reconstruction from $2\gamma$

\[ \cos \theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2} \]

missing Pt by two neutrinos = finite $\pi^0$ Pt

$\Rightarrow$ signal region on Pt - Z plane
History of the KOTO data taking

2015 run

2013 run
first physics run

2016-2018 run
data taking continues

Accumulated P.O.T.

×10^{18}

Beam Power (kW)

2012 Dec
2013 Dec
2014 Dec
2016 Jan
2016 Dec
2017 Dec
First physics run in 2013

A new search for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 X^0$ decays

J-PARC KOTO Collaboration

One candidate event observed consistent with BG expectation

$\rightarrow \text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8} (90\% \text{C.L.})$

Single Event Sensitivity = $1.28 \times 10^{-8}$ w/ only 100H data

cf. KEK E391a final best upper limit so far : SES = $1.11 \times 10^{-8}$
What we learned from the 2013 run
What we learned from the 2013 run

1. hadron cluster BG

2. neutron

halo-neutron: our ENEMY!

“pencil” beam

K_L, n, γ

go through beam hole

Beams profile (X[mm])

@ CSI surface

hit detector => BG source
What we learned from the 2013 run

1. hadron cluster BG

2. upstream π^0

3. K_L → π^+π^-π^0

π^0 → missing

π^± disappear @ vacuum pipe
Upgrades for the 2015 run

- **Halo-neutron**
  - Source of Hadron cluster BG and Upstream $\pi^0$ BG
  - Thinner vacuum window
    - $125\mu m \rightarrow 12.5\mu m$
  - Beam profile monitor for better beam alignment
    - $N_{\text{halo}} \sim 1/2$

- $K_L \rightarrow \pi^+\pi^-\pi^0$ BG
  - Low-mass beam pipe
    - SUS $\rightarrow$ Al
  - New scintillation counter
    - $N_{\pi^+\pi^-\pi^0 \text{ BG}} \sim 1/20$

- $\pi^\pm$ disappear at vacuum pipe

- $K_L \rightarrow \pi^+\pi^-\pi^0$ (BG)
  - $\pi^\pm$ (missing)

- $\pi^\pm$ (upstream $\pi^0$)

- $2\gamma$
Other detector upgrades: downstream region

High rate capability

- new in-beam charged veto

in-beam charged veto

beam

CSI

More photon detection efficiency

additional photon counters

lead/aerogel Cherenkov counters

# modules: 12 -> 16

new lead/acrylic Cherenkov counter

• wire chamber
• insensitive to neutron
※ original one was 3-mm-thick plastic scintillator

in-beam photon veto
the 2015 run analysis

• Single Event Sensitivity

• $K_L$-decay background

• Neutron induced background

➡ unblind the signal region
Single Event Sensitivity (SES)

KL flux from $K_L \rightarrow 2\pi^0$ analysis

Rec. $K_L$ mass

Data

$K_L \rightarrow 3\pi^0$ MC

$K_L \rightarrow 2\pi^0$ MC

N Decay $K_L : 1.46 \times 10^{11}$
(3000 < Z[mm] < 4700)

Acceptance : 0.52%

Single Event Sensitivity = $\frac{1}{(K_L \text{ yield}) \times (\text{Signal acceptance})}$

= $1.3 \times 10^{-9}$

×10 better sensitivity than that of the 2013 run

c.f. GN bound : <1.5×10$^{-9}$
$K_L \to \pi^+\pi^-\pi^0$ background

- low-mass beam pipe (SUS→Al)
- $\times 2$ reduction
- new scintillation counter
- $\times 10$ reduction

$N_{K_L \to \pi^+\pi^-\pi^0 \text{BG}} = 0.05 \pm 0.02$
$K_L \rightarrow 2\pi^0$ background

Additional photon counters
- lead/aerogel Cherenkov counters
- lead/acrylic Cherenkov counters

$N_{K_L \rightarrow 2\pi^0 \text{BG}} = 0.02 \pm 0.02$
Neutron induced background

3 types of background

1. Hit CSI
2. Hit upstream detector
3. Hit CV

halo neutron

Charged Veto (CV)
**Hadron cluster background**

- **1st Hit**
- **2nd Hit**

**Physics data**

**control sample**

- **Al plate (t=10mm) as a scattering source**
- **Special run to take control sample**

- **neutron**
- **n**

※ **Loose veto**
Reduction of the Hadron cluster BG

\[ K_L \rightarrow \pi^0 \nu \nu \] signal = 2 gammas on CSI + nothing

Hadron cluster BG = 2 clusters on CSI + nothing

need n-\( \gamma \) discrimination w/ CSI information

\[ \text{EM-cluster (\( \gamma \))} \]
\[ \text{Hadron-cluster (n)} \]

discrimination methods

• Cluster Shape Discrimination

• Pulse Shape Discrimination
n-γ discrimination with CSI

: Cluster Shape Discrimination

- **Shape χ² method** (used in 2013 run)
  \[
  \chi^2 \equiv \frac{1}{N} \sum_{i} \left( \frac{e_i}{E_{inc}} - \mu \right)^2
  \]
  if data is consistent with γ MC
  ➞ accept
  ➞ 1/300 BG reduction & 80% signal acceptance

- **Shape neural net method**
  Energy, Time of crystals as input variables
  Neutron
  Photon
  1/1500 neutron reduction with 90% signal acceptance

25×25 mm² crystal
50×50 mm² crystal
c.f. \( R_{Moliere} = 35.7 \text{mm} \)

Shower shape can be seen!
**n-γ discrimination with CSI**

: **Pulse Shape Discrimination**

- Waveform fitting

**Asymmetric Gaussian:**

\[ A(t) = |A| \exp \left( -\frac{(t - t_0)^2}{2\sigma(t)^2} \right), \]

\[ \sigma(t) = \sigma_0 + a(t - t_0) \]

- Neutron pulse has a longer tail

- Waveform of individual crystals of CSI stored with 125MHz digitizer

- Template of neutron/gamma events to calculate likelihood

![Graph showing waveform fitting and likelihood ratio](image)

- 1/10 BG reduction & 90% signal acceptance

- Neutron-rich
Hadron cluster background

\[ N_{\text{Had. BG}} = 0.24 \pm 0.17 \]
Upstream-\(\pi^0\) background

Simulation

- smaller visible energy
  \(\rightarrow Z_{\text{vtx}}\) shift to downstream
- "\(\gamma + n\)" event

\[ N_{\text{Upstream-}\pi^0\text{ BG}} = 0.04 \pm 0.03 \]
CV-Eta background : Mechanism

\[ \cos \Omega = 1 - \frac{m_{\pi^0}^2}{2E_1E_2} \]

\( \Omega \) is calculated to be smaller because \( m_\eta > m_\pi \) (\( m_\eta \sim 4m_\pi \)).

\( \rightarrow \) rec. \( Z \) goes upstream.

\( Z=6148 \)

\( Z=5842 \)
New Cut for the CV-Eta BG

η-χ² cut:
- if the cluster shapes are consistent with the assumption that they are derived from $\eta \rightarrow 2\gamma$ decay at CV, the event is rejected
- good consistency = small $\chi^2$ value

$N_{CV-\eta \ BG} = 0.03 \pm 0.02$
Background summary

Observed Estimated

<table>
<thead>
<tr>
<th>BG source</th>
<th># of BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to 2\pi^0$</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>$K_L \to \pi^+\pi^-\pi^0$</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>Hadron Cluster</td>
<td>0.24 ± 0.17</td>
</tr>
<tr>
<td>Upstream-\pi^0</td>
<td>0.04 ± 0.03</td>
</tr>
<tr>
<td>CV-\eta</td>
<td>0.03 ± 0.02</td>
</tr>
<tr>
<td>others</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.40 ± 0.18</td>
</tr>
</tbody>
</table>
# Results

<table>
<thead>
<tr>
<th>π^0 Pt [MeV/c]</th>
<th>Rec. π^0 Z [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>324.4 ±2.7</td>
</tr>
<tr>
<td>0</td>
<td>0.40 ±0.18</td>
</tr>
<tr>
<td>1</td>
<td>1.40 ±0.15</td>
</tr>
<tr>
<td>0</td>
<td>0.27 ±0.15</td>
</tr>
<tr>
<td>0</td>
<td>0.11 ±0.06</td>
</tr>
<tr>
<td>1</td>
<td>0.54 ±0.16</td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

S.E.S. : 1.3 ×10^-9

Preliminary
Results

No candidate event observed

S.E.S. : $1.3 \times 10^{-9}$
Results

\[ \rightarrow \text{Br}(K_L \rightarrow \pi^0 \nu \nu) < 3.0 \times 10^{-9} \]

(90\% C.L.)

S.E.S. : 1.3 \times 10^{-9}

※ systematic uncertainty is not taken into account

No candidate event observed
Results

\[
\text{Br}(K_L \rightarrow \pi^0 \nu\nu) < 3.0 \times 10^{-9} \quad (90\% \text{ C.L.})
\]

※ systematic uncertainty is not taken into account

upper limit by E391a : 2.6 \times 10^{-8} (90\% \text{ C.L.})

~ one order of magnitude improvement !
Prospects: 2016-2018 run

- additional $\times 1.5$ physics data
  $\Rightarrow$ SES $\sim 5 \times 10^{-10}$ (combined with 2015 run data)

- $\times 10$ control samples for the hadron cluster BG
  $\Rightarrow$ improvement of the n-$\gamma$ discrimination

additional photon counter
(13.5$X_0$+5$X_0$) $\Rightarrow K_L \rightarrow 2\pi^0$ BG $\downarrow 1/3$
Prospects: Detector upgrades during THIS summer shutdown

CSI upgrade to reduce the hadron cluster BG

Now

Attach MPPCs in this summer 2018

6 × 6 mm² S13360-6050CS (HPK)

$\gamma$

$X_0 \sim 2 \text{ cm}$

$n$

interaction length $\sim 40 \text{ cm}$

locate interaction Z position
Prospects: Detector upgrades during THIS summer shutdown

CSI upgrade to reduce the hadron cluster BG

Now

Attach MPPCs in this summer 2018

6 x 6 mm²
S13360-6050CS (HPK)

Timing difference (ns)

locate interaction Z position $\Rightarrow N_{BG} \sim 1/10$

CsI crystal

upstream

MPPCs

interaction length $\sim 40$ cm

$X_0 \sim 2$

$\gamma$

$\eta$

n reduction: 9%

after applying cluster shape cut

Simulation
Prospects: Future run

- expect $O(10^{-11})$ SES with the next 3-year data
  - beam power 50→90kW and more

- aim to SM sensitivity
  - better beam condition by the power supply upgrade of the accelerator
Summary

• $K_L \rightarrow \pi^0 \nu \nu$ search at KOTO

• No candidate event in the 2015 run data
  • $\text{Br}(K_L \rightarrow \pi^0 \nu \nu) < 3.0 \times 10^{-9}$ @90% C.L. (preliminary)
    • one order of magnitude improvement