Search for the rare decay

\[ K_L \to \pi^0 \nu \bar{\nu} \] at J-PARC

-New results from the KOTO experiment-

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$K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay

- Breaks CP symmetry directly
- Small theoretical uncertainty: 2%
- Suppressed in the SM

$\rightarrow$ Sensitive to New Physics

$Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$

- Direct limit (KEK E391) $2.6 \times 10^{-8}$
- Grossman-Nir bound
  - Indirect limit from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
  - $Br(K_L) < 4.4 \times Br(K^+)$
  - $< 1.5 \times 10^{-9}$
- Standard model: $3.0 \times 10^{-11}$

Below Grossman-Nir bound

Large room for New Physics.
KOTO experiment

- Study of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC 30GeV Main Ring.

Collaboration photo at J-PARC (June. 2018)
Experimental principle

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay

Neutral beam line

target

proton

“2 $\gamma$ + Nothing + $Pt$”

Assuming 2 $\gamma$ from $\pi^0$,
Calculate z vertex.

$M^2(\pi^0) = 2E_1E_2(1 - \cos \theta)$

Calculate $\pi^0$ transverse momentum
Results of first physics run

- 2013 100h data (PTEP 2017 021C01)
- Observed/Expected=1/0.34
- BR($K_L \rightarrow \pi^0 \nu \nu$)<$5.1 \times 10^{-8}$ (90% C.L.)

(1) Pion produced at detector upstream.  
(2) Particles missing in the downstream gap  
(3) Neutron direct hit on CsI

Largest background
Run history

First Physics run (2013 data)

New results from the 2015 data

Analysis ongoing
Detector upgrade after 2013 run

In-beam Charged Veto (Wire chamber CF$_4$+C$_5$H$_{12}$ gas)

Capable for higher beam power

Increase detection efficiency for charged particles

Scintillator counters

Increase photon detection efficiency

Additional photon counters
Features of 2015 data analysis

- Larger statistics
  - (First physics run)\times 20
- Better control samples to study neutron BG
- Detector upgrade
  - Installed several detectors to reduce kaon-decay BG
Halo neutron background

-Collected control samples to study of neutron clusters

BG mechanism in physics run

Special run to take control sample

With 10mm Al plate inserted in the neural beam
New methods for rejecting neutron Background

Cluster Shape Discrimination

- Use cluster energy and timing information as inputs of neural net

- Training samples
  Signal: Signal MC
  BG : Special run data
New methods for rejecting neutron Background

Pulse Shape Discrimination

\[ |A| \exp \left( -\frac{(t - t_0)^2}{2(a(t - t_0) + \sigma_0)^2} \right) \]

Neutron has wider pulse from hadronic shower

- Make templates. (\(\gamma\) and neutron)
- Calculate likelihood ratio
New methods for rejecting neutron Background

Neutron Sample  2013 selection  2015 selection

- #(Neutron background) reduced by a factor of 10.
- The number of neutron background in the signal box is 0.24±0.17
Halo neutron hitting upstream detector

\[ nA \rightarrow \pi^0 X \]

- The number of upstream events expected in the signal box
  - 0.04±0.03
Halo neutron hitting the materials near the CsI Calorimeter

Charged veto counters

Csl calorimeter

$\eta$ event MC

$\pi^0$ event MC
New cut for BG events caused by $\eta$

- Check cluster shape under the assumptions
  - $\eta$ mass, Vertex position = Charged veto counter (CV)
- After applying $\eta - \chi^2$ cut, the number of $\eta$ background events expected in the signal box is $0.03 \pm 0.02$
$K_L \rightarrow \pi^+ \pi^- \pi^0$ background

- Thinner vacuum pipe
  - $\#$(Background) became 1/2.
- Installed new scintillator counters
  - $\#$(Background) became 1/10. (0.05±0.02)

Observed Expected from $K_L \rightarrow \pi^+ \pi^- \pi^0$ MC
$K_L \rightarrow 2\pi^0$ background

Installed additional photon counters

The number of $K_L \rightarrow 2\pi^0$ background is $-0.02 \pm 0.02$
Results of 2015 analysis

Summary of background inside the signal box

<table>
<thead>
<tr>
<th>background source</th>
<th>#BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halo neutron hitting CSI</td>
<td>0.24±0.17</td>
</tr>
<tr>
<td>Halo neutron hitting upstream detectors</td>
<td>0.04±0.03</td>
</tr>
<tr>
<td>η background</td>
<td>0.03±0.02</td>
</tr>
<tr>
<td>KL→π+π−π0</td>
<td>0.05±0.02</td>
</tr>
<tr>
<td>KL→2π0</td>
<td>0.02±0.02</td>
</tr>
<tr>
<td>other BG sources</td>
<td>0.02±0.02</td>
</tr>
<tr>
<td>Sum</td>
<td>0.40±0.18</td>
</tr>
</tbody>
</table>

S.E.S: \(1.3 \times 10^{-9}\)  
cf. Grossman-Nir bound <1.5e-9
Open the signal box
Open the signal box

• No signal candidate observed
Open the signal box

- No signal candidate observed
- $\text{BR} < 3.0 \times 10^{-9} \text{ @90\%C.L.}$ with Poisson statistics
Open the signal box

- No signal candidate observed
- \( \text{BR} < 3.0 \times 10^{-9} @ 90\% \text{C.L.} \)

Improved by One order of magnitude

S.E.Sx 2.3 with Poisson statistics
Prospect

- 2016-2018 data analysis is ongoing
- 1.5x (physics data), 10x (neutron data)
  -> With 2015-2018 data, we can reach S.E.S of $5 \times 10^{-10}$
- From this summer
  - We will upgrade detectors to suppress background.
    - Ex. Calorimeter upgrade against neutron BG.
  - We will improve analysis to recover acceptance
  - Beam power will increase from 50kW to 90kW gradually, after installing a new production target to the Hadron Hall in 2019.
  -> We aim to go below $10^{-10}$ in a timely manner
Summary

- The KOTO experiment studies the $K_L \rightarrow \pi^0 \nu \nu$ decay.
- No signal candidate observed in 2015 data.
  - $\text{BR} < 3.0 \times 10^{-9}$ @90% C.L.
    - Improved the current upper limit by one order of magnitude
- 2016-2018 data analysis is ongoing
- We will upgrade detectors and improve analysis to get further sensitivity
• Back up
Calorimeter upgrade

Both-end readout

Timing Difference $\Delta T = T(\text{MPPC}) - T(\text{PMT})$

$\Delta T (\gamma) < \Delta T (\text{neutron})$ expected

Details in poster presentation by N. Hara (Osaka U)
Calorimeter upgrade

4096 MPPCs  1024 cables

4-MPPC connection

Two types of crystals

summing up

quartz plate

coaxial cable (1mm φ)

Amp Controller

Vacuum

125MHz ADC
Remaining $K_L \rightarrow \pi^+ \pi^0$ in MC

Interaction occurs at:
- membrane between low and high vacuum
- G10 support for membrane
- vacuum flanges

→ New downstream CV (2018 upgrade)

Liner charged veto inside these structures is effective to reduce this background
KOTO detector since 2016

* Inner barrel detector (IB) installed
  - Additional 5 $X_0$ thickness in barrel region
  - Fine sampling (sandwich of 1mm lead and 5mm scintillator)
# Improvement against BG

<table>
<thead>
<tr>
<th>BG source</th>
<th>#BG 2015 analysis</th>
<th>2016-2018 data</th>
<th>After 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halo neutron hitting CSI</td>
<td>0.24±0.17</td>
<td>Improve cluster shape discriminant with large amount of neutron samples</td>
<td>Improve cluster shape discriminant Calorimeter upgrade</td>
</tr>
<tr>
<td>Halo neutron hitting NCC</td>
<td>0.04±0.03</td>
<td>Reducing the upstream side of the signal box Consider rejection of neutron cluster by PSLH. Improve cluster shape discriminant</td>
<td>Improve cluster shape discriminant Calorimeter upgrade Neutron detector at downstream*</td>
</tr>
<tr>
<td>$\eta$ BG</td>
<td>0.03±0.02</td>
<td>CSD with deep learning for CV-$\eta$ BG Remove G10 pipe in front of CSI</td>
<td>Neutron detector at downstream* Implement a new Al target in front of CV*</td>
</tr>
<tr>
<td>KL-&gt;$\pi + \pi - \pi 0$</td>
<td>0.05±0.03</td>
<td>Use tighter threshold for CC04-CC06 (3MeV-&gt;1MeV)</td>
<td>install new charged veto counter inside vacuum tank</td>
</tr>
<tr>
<td>KL-&gt;2$\pi 0$</td>
<td>0.02±0.02</td>
<td>add additional barrel detector(IB)</td>
<td>add additional barrel detector(IB)</td>
</tr>
<tr>
<td>Masking KL-&gt;3pi0</td>
<td>0.01±0.01</td>
<td>Pulse shape analysis</td>
<td>Pulse shape analysis Install 500MHz FADC for high rate counter like FB</td>
</tr>
<tr>
<td>Scattered KL-&gt;2gamma</td>
<td>0.01±0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sentences with asterisk are under discussion.