A future $K_L \rightarrow \pi^0 \nu \nu$ experiment at J-PARC

Tadashi Nomura (KEK/J-PARC)
Sensitivity is a function of:
- Primary (proton) beam power
- KL yield @ experimental area
- Decay probability
- Acceptance for detection
- Running time
Current experiment “KOTO”

Proton beam power: 51kW (as of 2019)

In the Hadron Facility

Slow extraction (SX) to Hadron facility

SX cycle

<table>
<thead>
<tr>
<th>0</th>
<th>2</th>
<th>5.2</th>
<th>5.2+2 (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam</td>
<td>beam</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>
From Accelerator report for J-PARC PAC in July 2019

**J-PARC mid-term plan**

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**Mid-term plan of MR**

**FX:** The higher repetition rate scheme: Period 2.48 s → 1.3 s for 750 kW.  
(= shorter repetition period) → 1.16 s for 1.3 MW  
**SX:** Mitigation of the residual activity for 100kW

<table>
<thead>
<tr>
<th>Event</th>
<th>New buildings</th>
<th>HD target</th>
<th>Long shutdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>FX power [kW]</td>
<td>475</td>
<td>&gt;480</td>
<td>&gt;480</td>
</tr>
<tr>
<td>SX power [kW]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Cycle time of main magnet PS</td>
<td>2.48 s</td>
<td>2.48 s</td>
<td>2.48 s</td>
</tr>
<tr>
<td>New magnet PS</td>
<td>Mass production installation/test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High gradient rf system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd harmonic rf system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring collimators</td>
<td>Add.collimators (2 kW)</td>
<td></td>
<td>Add.colli. (3.5kW)</td>
</tr>
<tr>
<td>Injection system</td>
<td>Kicker PS improvement, Septa manufacture /test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FX system</td>
<td>Kicker PS improvement, FX septa manufacture /test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SX collimator / Local shields</td>
<td>Local shields</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti ducts and SX devices with Ti chamber</td>
<td>Ti-ESS-1, (Ti-ESS-2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Target Upgrade

Current target

- Proton beam
- Gold (6-divided)
- Copper
- Stainless-steel tube
- Cooling water

Cross-sectional view

- Gold, copper, and stainless-steel tubes are bonded by HIP (Hot Isostatic Pressing)
- 66mm cross-sectional view of the target chamber

New target

- Cooling on both top and bottom

Acceptable beam power => up-to 95kW
New MR Power Supply

- Shorter cycle time (=higher repetition)
  - 5.2->4 sec for slow extraction (SX)

- Lower ripple noises
  => Higher beam power: toward 100kW

- Smooth SX beam
KOTO Sensitivity projection

- 4 month run/year scenario
- 2 month run/year scenario

Combined sensitivity of 2015-2018

For MR upgrades

http://www.lng.infn.it/wg/vus
Will KOTO reach enough?

- Given KL flux, running time, KOTO may reach close to the Standard Model sensitivity \((3 \times 10^{-11})\) but it will take long time, by 2025 or around.

- In addition, it is not enough to claim the OBSERVATION.
Next step

- We now start considering seriously a new experiment that can observe 100 SM events.
- A concept was described in the KOTO proposal in 2006, as “Step-2”.
Keys for KOTO Step-2

- To obtain higher kaon flux, a smaller production angle is preferable; 16 degree in KOTO => 5 degree

- To catch more kaon decays, a larger and longer detector is necessary 2m-diameter end-cap in KOTO => 3m 2m-long fiducial region in KOTO => 13m (A harder KL spectrum is better.)
**Yield, n/K vs angle**

(Target simulation)

**Yield**

<table>
<thead>
<tr>
<th>neutron</th>
<th>En &gt; 1 MeV</th>
<th>En &gt; 100 MeV</th>
<th>En &gt; 300 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>thk</td>
<td>Entries 130601</td>
<td>Mean 5.575</td>
<td>RMS 4.755</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>KL</th>
<th>En &gt; 1 MeV</th>
<th>En &gt; 100 MeV</th>
<th>En &gt; 300 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>thk01</td>
<td>Entries 288244</td>
<td>Mean 5.526</td>
<td>RMS 5.056</td>
</tr>
</tbody>
</table>

5 degree
Step 2
16 degree
KOTO

5 degree
Step 2
16 degree
KOTO
Experimental hall now

KOTO is sitting here

To accommodate our ideas, a facility upgrade is necessary.

Gray region: cutaway view inside the radiation shield
Hadron Hall Extension

Extend Hadron Experimental Facility
More targets, more beam lines

KOTO step-2 location
Dedicated annex behind the dump
Hadron Hall Extension

- The Extension of the Hadron Facility is a joint project with nuclear physics community.
- KOTO step-2 is one of the flagships of the project.
- It is on the list of KEK future large-scale projects, though the assigned priority is not so high at this moment.
- Making a staging plan toward full construction.
Possible beam line

Minimum set as KOTO
- 2 stages of collimator
- 1 sweeping magnet
- Photon absorbing (Pb)

Experimental area

43m from the target, behind the proton dump
Working assumption (Beam)

<table>
<thead>
<tr>
<th></th>
<th>BEAM</th>
<th>KOTO</th>
<th>Step-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power</td>
<td>(50→100kW)</td>
<td>100kW</td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>60mmL gold</td>
<td>102mmL gold</td>
<td></td>
</tr>
<tr>
<td>Production angle</td>
<td>16 degree</td>
<td>5 degree</td>
<td></td>
</tr>
<tr>
<td>Beam line length</td>
<td>20m</td>
<td>43m</td>
<td></td>
</tr>
<tr>
<td>Solid angle</td>
<td>7.8 μsr</td>
<td>4.8 μsr</td>
<td></td>
</tr>
</tbody>
</table>
KL flux and spectrum

At the exit of the beam line

Kaon spectrum

**Simulation result**

\[
N(KL) = \frac{1.1 \times 10^7}{2 \times 10^{13}} \text{ POT}
\]

\[
\Leftrightarrow \text{KOTO } N(KL) = \frac{\sim 4.2 \times 10^6}{2 \times 10^{13}} \text{ POT}
\]

\[
\text{cf. } 100 \text{kW} = \frac{100 \times 10^3}{1.6 \times 10^{-19}}/30 \times 10^9 = 2.1 \times 10^{13} \text{ protons/s}
\]
# Expected yield

<table>
<thead>
<tr>
<th>Photon</th>
<th>KL</th>
<th>POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;10 MeV</td>
<td>1.1x10^7/2x10^{13}</td>
<td>5x10^7/2x10^{13}</td>
</tr>
<tr>
<td>&gt;100 MeV</td>
<td></td>
<td>1x10^7/2x10^{13}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutron</th>
<th>KL</th>
<th>POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.1 GeV</td>
<td>3x10^8/2x10^{13}</td>
<td>2x10^8/2x10^{13}</td>
</tr>
<tr>
<td>&gt;1 GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tough for in-beam detectors ...
Beam profile and halo

Simulation result

Neutron profile (at end-cap detector)

N(halo)/N(core) = 1.8 × 10^{-4}

Here, core (halo) = “inside (outside) ± 10 cm”
## Working assumption (Detector)

<table>
<thead>
<tr>
<th>Detector</th>
<th>KOTO</th>
<th>Step-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-cap detector</td>
<td>2m diameter</td>
<td>3m diameter</td>
</tr>
<tr>
<td>Detector length (up-to end-cap)</td>
<td>~6m</td>
<td>~20m</td>
</tr>
<tr>
<td>Length of the Decay region</td>
<td>~2m</td>
<td>~15m</td>
</tr>
<tr>
<td>Beam hole at end-cap</td>
<td>~15cm sq.</td>
<td>~20cm sq.</td>
</tr>
</tbody>
</table>
Detector model

KOTO

KL

2γ

2m

KOTO

Step-2

KL

2γ

2m

3m

15m
Sensitivity and BG

- Estimated by using “fast simulation”
- Using inefficiency function for each assumed detector type.
- Basic kinematic cuts used in KOTO are imposed.

NOT YET OPTIMIZED; JUST FOR DISCUSSION
Signal in PT-Z plot

Scaled to equivalent protons for 100kW, 3 snow-mass year running

Here a simple rectangular signal box (Z=2 to 18m) is considered, but ...
In real life, Backgrounds!

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

\[ K_L \rightarrow \pi^+\pi^-\pi^0 \]

Neutron
Backgrounds!

Assumed Veto threshold = 1MeV
(and 6 p.e. for in-beam detector)

\[ K_L \rightarrow 2\pi^0 \]
75 events

\[ K_L \rightarrow \pi^+\pi^-\pi^0 \]
\(~2600\) events!

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

\[ K_L \rightarrow \pi^+\pi^-\pi^0 \]

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

Full simulation for neutron interaction with the calorimeter
Neutron

125 events (*)

Assumed Veto threshold = 1MeV
(and 6 p.e. for in-beam detector)

(*) Achieved reduction of cluster shape cuts in 2016-18 data analysis \((10^{-6})\) is assumed.
Pentagon signal box

Scaled to equivalent protons for 100kW, 3 snow-mass year running

Pentagon signal box
- Cutting Z closed to the calorimeter
- Cutting low PT in large Z

\( K_L \rightarrow \pi^0 \nu \nu \)

62 events
BG with pentagon box

\( K_L \rightarrow 2\pi^0 \)
61 events

\( K_L \rightarrow \pi^+\pi^-\pi^0 \)
11 events

Neutron
21→2 events (***)

(***) In addition to 10\(^{-6}\) reduction by cluster shape cuts, the both-end readout calorimeter will provide 10\(^{-1}\) reduction.
Sensitivity and BG

- \(~60\) SM events with S/N\(^{-1}\)
  will be a baseline number.

- To be considered
  - In-beam detector performance
  - Signal loss due to accidental hits
  - ...

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Yet another idea?

- The base line plan for Step 2 requires the extension of the facility.

- BUT, it as a whole will take a time and a large cost: 7(?) years and ~200(?) Oku-Yen

- It is better we have an option that can be done without (full) extension...
Yet another idea?

"barrel detection"

- Photon veto
- Photon tracker
- Charged particle veto

KL

- Decay probability: KOTO 3% -> THIS 19% ×18 gain
- Geometrical acceptance: KOTO 27% -> THIS 72%

Pros: Current beam line can be used. Low momentum is OK. Extendable.

Cons: What detector??
Summary

We start considering a future $K_L \rightarrow \pi^0 \nu\nu$ experiment at J-PARC that can observe $O(100)$ SM events.

With a simple working model, we expect $\sim 60$ SM events with S/N$\sim 1$ with 100kW beam and 3 snow-mass years running.
Summary

- A base plan is considered as a part of the hadron facility extension project. We also consider a way to make new experiments without the extension as an option.

- For realization, many things we have to consider, many ideas we need.

PLEASE JOIN US and have fun to think and carry out this challenging subject.