KOTO experiment: a measurement of the branching ratio of rare decay

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

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On behalf of KOTO collaboration
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Outline

• Overview
• Physics motivation
• Experimental strategy
• E391a challenges
• Detector status
• 1st physics run and the radiation accident
Overview

- KOTO (K⁰ at Tokai) experiment is designed to measure the branching ratio of rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$. The SM branching ratio prediction is $2.43(39)(06) \times 10^{-11}$ (Phys.Rev.D.034030(2011)), with a very small theoretical uncertainty of 2.5%.

- The facility to generate $K_L$ beam for KOTO is the 50 GeV proton synchrotron (Main Ring energy is 30 GeV) in J-PARC, Tokai-mura, Japan.


KOTO has a collaboration of 65 people from 16 institutes from 5 countries.
Physics Motivation I

• Fundamental test of the Standard Model
  – It’s a Flavor Changing Neutral Current (FCNC) process induced through electroweak penguin and box diagrams with $t$ quark internal loop.
  – Direct CP violating process: branching ratio proportional to the square of the imaginary part of CKM matrix

$V = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)$

$Br(K_L^0 \to \pi^0\nu\bar{\nu}) = 6.87 \times 10^{-4} \times Br(K^+ \to \pi^0 e^+\nu) \times A^4\lambda^8\eta^2 X^2(x_t)$

$= (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$

$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0.$
Physics Motivation II

• Beyond Standard Model (BSM) extensions
  – The decay is dominated by electroweak loop diagrams, thus sensitive to short distance (high energy scale) physics. Therefore, it’s a good probe of high energy scale physics using a low energy process.
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GOAL : $10^{-13}$ sensitivity of branching ratio measurement
Experimental strategy

• Select events with **only two photons and nothing else.** (Calorimeter + hermetic veto)
• Using the information of **deposit energy** ($E_i$) and **position** ($r_i$) of the two photons, reconstruct the $\pi^0$ decay point ($Z_{\text{vertex}}$) (which is the $K_L$ decay point), and $P_T$.
• Define a signal region in $P_T$-$Z_{\text{vertex}}$ plane to find the signal.

$K_L$ pencil beam: put a constraint on kinematic reconstruction

\[
\cos \theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}
\]
Pilot E391a and its challenges

- E391a gives an upper limit measurement of $Br < 2.6 \times 10^{-8}$ at 90% Confidence level. (Phys. Rev. D, 072004 (2010))
- Neutron interaction with detectors close to the beam is the biggest background. At a single event sensitivity of $1.1 \times 10^{-8}$.

How to make an improvement of 1000 times to reach SM sensitivity
- Halo neutron suppression
- $K_L \rightarrow 2\pi^0$ background suppression
- New readout electronics

<table>
<thead>
<tr>
<th>Background source</th>
<th>Estimated number of BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halo neutron BG</td>
<td></td>
</tr>
<tr>
<td>CC02-$\pi^0$</td>
<td>$0.66 \pm 0.39$</td>
</tr>
<tr>
<td>CV-$\pi^0$</td>
<td>$&lt;0.36$</td>
</tr>
<tr>
<td>CV-$\eta$</td>
<td>$0.19 \pm 0.13$</td>
</tr>
<tr>
<td>$K_L^0$ decay BG</td>
<td></td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^0\pi^0$</td>
<td>$(2.4 \pm 1.8) \times 10^{-2}$</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \gamma\gamma$</td>
<td>Negligible</td>
</tr>
<tr>
<td>Charged modes</td>
<td>Negligible ($O(10^{-4})$)</td>
</tr>
<tr>
<td>Backward $\pi^0$</td>
<td>$&lt;0.05$</td>
</tr>
<tr>
<td>Residual gas</td>
<td>Negligible ($O(10^{-4})$)</td>
</tr>
<tr>
<td>Total</td>
<td>$0.87 \pm 0.41$</td>
</tr>
</tbody>
</table>
Beam line

- 30 GeV accelerator
  - Higher beam intensity, $K_L$ yield
  - Large extraction angle
- Re-designed collimator systems to suppress halo neutron.

<table>
<thead>
<tr>
<th>J-PARC E14 KOTO</th>
<th>KEK-E391a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary proton energy</td>
<td>30 GeV</td>
</tr>
<tr>
<td>Proton intensity (spill)</td>
<td>$2 \times 10^{14}$</td>
</tr>
<tr>
<td>Spill-length/repetition</td>
<td>0.7 s / 3.3 s</td>
</tr>
<tr>
<td>Extraction angle</td>
<td>16 deg.</td>
</tr>
<tr>
<td>$K_L$ yield (spill)</td>
<td>$8.1 \times 10^6$</td>
</tr>
<tr>
<td>Average $P_{K_L}$</td>
<td>2.1 GeV/c</td>
</tr>
<tr>
<td>$n/K_L$ ratio</td>
<td>6.5</td>
</tr>
</tbody>
</table>

The ratio of halo neutron/$K_L$ is suppressed by a factor $>200$, comparing with E391a.
Detectors

Diagram showing the layout of various detector components, including CsI calorimeter, decay region, and vacuum chamber.
CsI Calorimeter

- CsI Calorimeter is the endcap detector to measure photon energy and position.
- Some upgrade from E391a:
  - Finer granularity using KTeV CsI crystals. -> better position resolution
    - 25 * 25 mm² and 50 * 50 mm²
    - 2716 readout channels in total
  - Longer Length -> reduce photon punch-through
    - 16X₀ -> 27 X₀
  - Improve π⁰ reconstruction:

Estimated by sim.

KOTO CsI

e391a CsI

Reconstructed π⁰ vertex
Charged Veto (CV)

- Charged Veto is one endcap detector vetoing charged decay. Ke3, Kμ3, π⁺ π⁻ π⁰ decay.
- 2 planes of plastic scintillator
  - 2m diameter, 3mm thick
  - Wavelength Shift fiber and MPPC readout
  - Light material to reduce neutron interaction
  - <10⁻⁶ inefficiency required
Main Barrel (MB)

- Main Barrel (MB) cover the decay region
  - Plastic scintillator and lead sandwich structure
  - WLS fiber and two end PMT readout
  - 14 X0
- Main background: $K_L \rightarrow 2\pi^0$ with one or two $\gamma$ escaped MB.
- To reduce inefficiency, one MB upgrade is to insert 5 X0 thickness of Pb/scintillator.

Main Barrel (Pb+scinti): same as of E391a

Main Barrel photon detection inefficiency
Main Barrel (MB)

- Main Barrel (MB) cover the decay region
  - Plastic scintillator and lead sandwich structure (14 $X_0$)
  - WLS fiber and two end PMT readout
- Main background: $K_L \rightarrow 2\pi^0$ with one or two $\gamma$ escaped MB.
- To reduce inefficiency, one MB upgrade is to insert 5 $X_0$ thickness of Pb/scintillator.

### Main Barrel photon detection inefficiency

![Graph showing inefficiency vs. incident gamma energy (GeV)](image)

<table>
<thead>
<tr>
<th></th>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td>3.42±0.02</td>
<td>&gt; 3.42±0.02</td>
</tr>
<tr>
<td>$2\pi^0$ bkg</td>
<td>2.56±0.19</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>due to Main Barrel</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>other detectors</td>
<td>0.24</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Neutron Collar Counter (NCC)

- NCC is the veto detector at the exit of FB close to the beam line.
- NCC is made up of undoped CsI crystals segmented along the z axis to differentiate neutron from photon based on shower shapes.
- Two functions:
  - veto events with halo-neutron interactions. **Common readout**
  - Measure the amount of halo-n and energy spectrum to estimate background. **Individual readout**
Beam Hole Charged Veto (BHCV) & Beam Hole Photon Veto (BHPV)

- BHCV and BHPV are beam hole detectors downstream to catch the particles escaping the beam hole so as to complete the hermeticity.
- Due to Main Barrel and CV inefficiency, the BHCV will catch the $\pi^+ \pi^-$ to reduce the $K_L \rightarrow \pi^+ \pi^- \pi^0$ background. BHPV will catch the extra photon to reduce the $K_L \rightarrow 2\pi^0$ background.
- BHCV: scintillator plate.
- BHPV: aerogel Cerenkov detectors.
Data Acquisition system

- Challenges for rare decay experiment DAQ: high timing resolution; high data rate.
- Waveform sampling ADC front-end (0.1ns timing resolution)
- 3-tier pipeline trigger system

Spill structure: 2s (beam on)/4s (beam off)
Timeline of KOTO

- **Beamline construction finished (2009 Aug)**
- **CsI calorimeter stacking finished (2010 Feb)**
- **Charged Veto installation (2012 June)**
- **NCC installation (2012 Nov)**
- **Main Barrel installation (2012 Dec)**
- **Sub detectors (CC04 etc.) Installation (2012 Dec)**
- **Closing vacuum chamber (2012 Dec)**
- **FB installation (2012 Nov)**
- **2013 Jan engineering run**
- **1st physics run 2013 June**
Results from 2013 January engineering run

- $K_L \rightarrow 3\pi^0$ reconstruction
  - Good statistics 20%
  - Studying CsI performance, reconstruction method and MC.
- $K_L \rightarrow 2\pi^0$ reconstruction
  - Main background
  - Good tool for studying veto performance
**1st Physics run (May-June 2013)**

- The original plan for the KOTO physics run was to reach the Grossman-Nir bound sensitivity by running for a month.
- A radiation accident occurred in Hadron Hall on May 23rd. The data taking was terminated after an integrated Protons on Target (P.O.T) of $1.6 \times 10^{18}$.
- We estimate to have better sensitivity than E391a with this data set.
Conclusion

• KOTO experiment is dedicated to observe rare decay of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ and measure its branching ratio at high sensitivity to test SM and BSM extensions.

• In 2012, all the sub-detectors were installed. And two engineer runs during 2013 January and April proves that all detectors are well understood.

• Physics run started in May, but was terminated early due to the radiation accident of the Hadron Hall on May 23rd. Accumulated POT was $1.6 \times 10^{18}$. From this data set, we expect to get better sensitivity than E391a.
backup
**KOTO sensitivity estimate and BG budget**

<table>
<thead>
<tr>
<th>Source</th>
<th>GEANT4 value</th>
<th>new value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L^0$ flux/ 2×10^{14} P.O.T</td>
<td>7.4 × 10^6</td>
<td>1.94 × 10^7</td>
</tr>
<tr>
<td>P.O.T</td>
<td>1.8 × 10^{21}</td>
<td>1.8 × 10^{21}</td>
</tr>
<tr>
<td>decay probability</td>
<td>4.0%</td>
<td>3.9%</td>
</tr>
<tr>
<td>geometrical acceptance</td>
<td>28%</td>
<td>27%</td>
</tr>
<tr>
<td>cut efficiency</td>
<td>23%</td>
<td>22%</td>
</tr>
<tr>
<td>acceptance loss</td>
<td>72%</td>
<td>76%</td>
</tr>
<tr>
<td>sensitivity</td>
<td>2.1 × 10^{-11}</td>
<td>1.0 × 10^{-11}</td>
</tr>
<tr>
<td>number of signal event</td>
<td>1.2</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 7.2: Summary of the expected numbers of the signal and backgrounds.

<table>
<thead>
<tr>
<th>Source</th>
<th>GEANT4 value</th>
<th>new value</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal</td>
<td>$K_L^0 \rightarrow \pi^0\nu\bar{\nu}$</td>
<td>1.16±0.01</td>
</tr>
<tr>
<td>$K_L^0$ decays</td>
<td>$K_L^0 \rightarrow 2\pi^0$</td>
<td>0.74±0.02</td>
</tr>
<tr>
<td></td>
<td>$K_L^0 \rightarrow \pi^+\pi^-\pi^0$</td>
<td>0.05±0.01</td>
</tr>
<tr>
<td></td>
<td>$K_L^0 \rightarrow \pi^\pm e^\mp\nu$</td>
<td>0.04±0.01</td>
</tr>
<tr>
<td>halo neutron</td>
<td>NCC-π^0</td>
<td>0.05±0.02</td>
</tr>
<tr>
<td></td>
<td>CV-π^0</td>
<td>0.04±0.04</td>
</tr>
<tr>
<td></td>
<td>CV-η</td>
<td>0.01±0.01</td>
</tr>
<tr>
<td>S/N</td>
<td>1.25</td>
<td>1.49</td>
</tr>
</tbody>
</table>