Present status of the search for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay with the KOTO detector at J-PARC

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On behalf of the KOTO collaboration

APS DPF Meeting, August 3, 2017
KOTO Experiment

The experiment brings together over 50 collaborators from 16 different institutions

July ’17 collaboration meeting

Representation seen here: 16% female, 3% black
**Motivation**

$K_L \rightarrow \pi^0 \nu\nu$ ultra rare decay: Why is this important?

- The decay process proceeds via a flavor changing neutral current (FCNC)
- This process directly breaks CP
- Studying this decay is an excellent probe for New Physics (NP) beyond the Standard Model
- Results from this measurement will place tighter constraints or point to new physics

![Diagram of the decay process](image)

\[
\begin{align*}
BR(K^+ \rightarrow \pi^+ \nu\nu) & = (9.11 \pm 0.72) \times 10^{-11} \text{ (Buras et al. 2015)} \\
BR(K_L \rightarrow \pi^0 \nu\nu) & = (3.00 \pm 0.30) \times 10^{-11} \text{ (Buras et al. 2015)}
\end{align*}
\]

Small theoretical uncertainty
BR is proportional to CKM height

Fig. Unitarity triangle

Sources: Buras et al. JHEP 1511
BNL: E949 observed 2 clean events for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ~ BR ($17.3 \times 10^{-11}$)

Phys. Rev. Lett. 101, 191802 – Published 7 November 2008

Three events for the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ have been observed in the pion momentum region below the $K^+ \rightarrow \pi^+ \pi^0$ peak, $140 < P_\pi < 199$ MeV/c, with an estimated background of $0.93 \pm 0.17$(stat.$)$ $^{+0.32}_{-0.24}$(syst.$)$ events. Combining this observation with previously reported results yields a branching ratio of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ consistent with the standard model prediction.
Goals of KOTO

The KOTO experiment plans to report the first measurement of the branching ratio \( \text{Br}(K_L \rightarrow \pi^0 \nu \nu) \) with less than 10% uncertainty

- **KOTO Step 1:**
  - Make first observation of signal event (~10\(^{-12}\) sensitivity)
  - Search for new physics with BR higher than SM predictions

- **KOTO Step 2:**
  - Measure roughly 100 events (~10\(^{-13}\) sensitivity)
Brief history of search before KOTO

Advance in study enabled by detector R&D, computing, and accelerator technology

E391a experiment was impeded by limited veto capabilities and low beam power (~12GeV)

Branching ratio

<table>
<thead>
<tr>
<th>Year</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN</td>
<td>1.5 x 10^{-9}</td>
<td>Grossman-Nir limit</td>
<td>SM Prediction</td>
<td>new physics?</td>
</tr>
<tr>
<td>SM Prediction</td>
<td>10^{-10}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E391a final(\gamma\gamma)</td>
<td>10^{-12}</td>
<td>E391a &lt; 2.6 x 10^{-8}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

E731: FNAL
KeV: FNAL/KEK
E391a: KEK

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J-PARC facility

Experiment based at J-PARC (Japan Proton Accelerator Research Complex) in Tokai-mura

Hadron Experimental Facility (HEF)

- Intense 30 GeV proton beam with a 50% duty factor
- Secondary neutral beam is extracted (16°) and directed to KOTO detector
Chapter 1. Introduction

Three of the main neutral decays are used in simulation studies to compare with experimental data to calibrate the detectors, validate the simulation studies, and improve their identification to successfully distinguish the target decay. These decays, called normalization modes, are the $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$, $K^0_L \rightarrow 2\pi^0$, and $K^0_L \rightarrow 2\gamma$. Features such as the transverse momentum, and subsequently the COE, expected number of clusters, and other kinematic variables set these decays apart from the $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ target decay. This thesis will explore the $K^0_L \rightarrow 2\pi^0$ normalization mode and optimize the veto cuts that are applied during simulation studies, to improve the background to target signal ratio when studying this decay.

1.3.2 Halo Neutrons

While the other kaon decays provide a significant background, another major source of background comes from a different parent particle than the kaon. When neutrons react with residual

### Table. Branching ratios of various Kaon decays (PDG)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0_L \rightarrow \pi^0 e^+ \nu_e$</td>
<td>$0.4055 \pm 0.0011$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \pi^0 \mu^+ \nu_\mu$</td>
<td>$0.2704 \pm 0.0007$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow 3\pi^0$</td>
<td>$0.1952 \pm 0.0012$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \pi^+ \pi^- \pi^0$</td>
<td>$0.1254 \pm 0.0005$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow 2\pi^0$</td>
<td>$(0.864 \pm 0.006) \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow 2\gamma$</td>
<td>$(0.547 \pm 0.004) \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>$(2.49 \pm 0.39 \pm 0.06) \times 10^{-11}$</td>
</tr>
</tbody>
</table>

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**Fig. KOTO detector components**

**Background reduction is crucial!**

Two sub-system design:

- Cesium Iodide Calorimeter (CsI)
  - Main detector of the KOTO experiment

- Hermetic veto detectors
  - ~1000 channels
**Experimental method**

**Fig. Monte Carlo of signal and background distributions**

- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay
- **target** neutral pencil beam
- proton

"2 $\gamma$ + Nothing + $P_T$"

- Assuming $2\gamma$ from $\pi^0$
- Calculate decay vertex $M^2(\pi^0) = E_1E_2(1-\cos \theta)$
- Calculate $\pi^0$ transverse momentum

**Fig. Monte Carlo sample of signal distribution**

- Black: $K_L \rightarrow \pi^0 \nu \bar{\nu}$
- Red: $K_L \rightarrow 3\pi^0$
- Green: $K_L \rightarrow 2\pi^0$
- Blue: $K_L \rightarrow 2\gamma$
- Yellow: $K_L \rightarrow \pi^+\pi^-\pi^0$

**Signal Box**

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First physics run accepted by PTEP
arXiv: 160903637

Operation of Hadron facility was stopped.

Statistics ~2xRun49

Present analysis
Statistics ~20xRun49
We searched for the $CP$-violating rare decay of neutral kaon, $K_L \rightarrow \pi^0 \nu \bar{\nu}$, in data from the first 100 hours of physics running in 2013 of the J-PARC KOTO experiment. One candidate event was observed while 0.34 ± 0.16 background events were expected. We set an upper limit of $5.1 \times 10^{-8}$ for the branching fraction at the 90% confidence level (C.L.). An upper limit of $3.7 \times 10^{-8}$ at the 90% C.L. for the $K_L \rightarrow \pi^0 X^0$ decay was also set for the first time, where $X^0$ is an invisible particle with a mass of 135 MeV/c^2.

Results: Upper limit on BR ($K_L \rightarrow \pi^0 \nu \bar{\nu}$)

First Search: Upper limit on BR ($K_L \rightarrow \pi^0 X^0$)
First run takeaways

Summary of background estimation in the signal region

<table>
<thead>
<tr>
<th>background source</th>
<th>number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow 2\pi^0$</td>
<td>0.047 ± 0.033</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-\pi^0$</td>
<td>0.002 ± 0.002</td>
</tr>
<tr>
<td>$K_L \rightarrow 2\gamma$</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>halo neutrons hitting the calorimeter</td>
<td>0.18 ± 0.15</td>
</tr>
<tr>
<td>total</td>
<td>0.34 ± 0.16</td>
</tr>
</tbody>
</table>

- Expected/observed ~ 0.34/1
- Major contribution from neutrons ~70%

Background sources

1. Halo neutrons hitting NCC ($\pi^0$)

2. Halo neutrons hitting CsI

3. $K_L \rightarrow \pi^+\pi^-\pi^0$
Updates to reduce BG sources

Reduction of background sources

Source 1:
- Improved surface alignment of collimators
- Thinner vacuum window: 125 µm → 12.5 µm

Source 2:
- Specific experimental runs to study neutron induced events using an aluminum target
  - Neural Networks cut (Cluster Shape Discrimination) = 1/1500 reduction of original
  - Pulse-shape-likelihood cut = 1/10 reduction of original

Source 3:
- Added downstream detectors to identify particles escaping down beam pipe
  - Beam pipe charge veto = reduction by a factor of 10
  - New BHCV ~ reduced counting rate ~65% and accidental loss ~40%

Fig. Pulse-shape-likelihood ratio

Fig. Depiction of special Al run

Fig. Neural Net outcome of cluster shape cut

Fig. Reconstructed Pt vs. decay vertex position

Fig. Reconstructed Pt vs. decay vertex position
Single Event Sensitivity (SES) is a measure of signal (K_L → π^0νν) sensitivity.

Increased (SES) attributed to:

- Measured K_L flux and a wider signal region due to improved BG reduction methods and upgrades to detectors

\[
SES = \frac{1}{K_{\text{yield}} \cdot \text{Acceptance}_{\text{signal}}}
\]

### Estimated background events in Run 62

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_L→2π^0</td>
<td>0.04±0.03</td>
</tr>
<tr>
<td>K_L→π^+π^0</td>
<td>0.04±0.01</td>
</tr>
<tr>
<td>Halo neutrons hitting NCC</td>
<td>0.04±0.04</td>
</tr>
<tr>
<td>Halo neutrons hitting CSI</td>
<td>0.05±0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.17±0.05</td>
</tr>
<tr>
<td>Single Event Sensitivity</td>
<td>5.8 x 10^{-9}</td>
</tr>
</tbody>
</table>
Estimate of all 2015 data

Estimated single event sensitivity = $1.1 \times 10^{-9}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Run 62 Number of Events</th>
<th>All 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>$KL \rightarrow 2\pi^0$</td>
<td>0.04±0.03</td>
<td>0.07</td>
</tr>
<tr>
<td>$KL \rightarrow \pi^+\pi^-\pi^0$</td>
<td>0.04±0.01</td>
<td>0.23</td>
</tr>
<tr>
<td>Halo neutrons hitting NCC (upstream)</td>
<td>0.04±0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>Halo neutrons hitting CsI</td>
<td>0.05±0.02</td>
<td>0.34</td>
</tr>
<tr>
<td>$CV \pi^0$</td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>$CV \eta$</td>
<td></td>
<td>0.48</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.17±0.05</strong></td>
<td><strong>1.39</strong></td>
</tr>
</tbody>
</table>

Fig. Reconstructed $\pi^0$ Pt vs. decay vertex position

Black: Observed
Red: Expected
Summary

KOTO experiment performed at J-PARC is a dedicated search for the $K_L \rightarrow \pi^0 \nu \nu$ decay

Summary of KOTO first results

- KOTO Run 49 set a BR($K_L \rightarrow \pi^0 \nu \nu$) upper limit of $< 5.8 \times 10^{-8}$ (90% confidence)
- KOTO Run 49 set a BR($K_L \rightarrow \pi^0 \chi^0$) upper limit of $< 3.7 \times 10^{-8}$ (90% confidence), which is the first upper limit for $\chi^0$ mass of 135 MeV/c^2

Present status

- Collected a data set (2015 runs) ~ 20 times larger than the 2013 published results
- Confirmed that major BGs observed in 2013 run are well suppressed
- Analysis is in progress:
  - Focused on continued BG estimation and suppression
  - With the current calculated flux, we estimate a SES of $5.82 \times 10^{-9}$ for Run 62, twice that of Run 49, and a SES of $1.1 \times 10^{-9}$ for the entire 2015 data set
- After completing analysis of all 2015 data and finalization of SES, we expect to approach Grossman-Nir limit (theoretical model independent limit $\sim 1.5 \times 10^{-9}$)
Outlook

![Graph showing branching ratio versus year for various experiments: Littenberg, E731, E799, KTeV, E391a, KOTO, SM Prediction. Key points indicate experimental results with different experiments highlighted in different colors. The Grossman-Nir limit and SM Prediction are marked on the graph.]
Thank You
Supplemental
2015 Background Estimations

Data

<table>
<thead>
<tr>
<th>BG source</th>
<th>#BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow 2\pi^0$</td>
<td>0.07±0.07</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-\pi^0$</td>
<td>0.23±0.06</td>
</tr>
<tr>
<td>Upstream events</td>
<td>0.13±0.07</td>
</tr>
<tr>
<td>Hadron cluster</td>
<td>0.34±0.11</td>
</tr>
<tr>
<td>Other BG sources</td>
<td>Under estimation</td>
</tr>
</tbody>
</table>
Radius = 3m

Evacuated to $\sim 10^{-5}$ Pa to suppress background

Fig. Outer vacuum container houses all main KOTO detectors
Chapter 2: The KOTO Experiment

**Hadron Experimental Facility (HEF)**

- Intense 30 GeV proton beam with ~ a 50% duty factor
- Secondary neutral beam is extracted (16°) and directed to KOTO detector

---

**KOTO**

**Fig. 3D view of Hadron Experimental Facility**

**Fig. Target used for KOTO physics experiment**

**Fig. Layout inside Hadron Experimental Facility**

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KOTO neutral beam

Fig. Depiction of neutral beam line production

Target to detector distance = 21.5 m
KOTO detectors

Cesium Iodide Calorimeter (CsI)

- Main detector of the KOTO experiment
  - 2716 channels (undoped CsI crystals $X_0=27$) read out by PMTs

Hermetic veto detectors

- ~1000 channels

Fig. KOTO detector components

- Energy resolution ($\sigma_{E/E} = 0.99 \%/\text{GeV}^{1/2}$)
- Timing resolution ($\sigma_{t/E} = 0.13 \%/\text{GeV}^{1/2} \text{ ns}$)
- Position resolution ($\sigma_{d/E} = \sim 2.5 \%/\text{GeV}^{1/2} \text{ mm}$)
Inner Barrel

**New barrel photon veto (IB)**

- Aimed at reducing $K_L \rightarrow 2\pi^0$ background
- Is a sampling calorimeter (25 layers of 5 mm scintillators and 24 layers of 1 mm lead plates)
- Gained added another 5 $X_0$ to the MB 13 $X_0$ to decrease inefficiency of 4 gamma veto
- MC estimated suppression of $K_L \rightarrow 2\pi^0$ of 1/3

**Fig. Depiction of inner barrel placement within MB**

**Fig. Inner Barrel**

**Data $K_L \rightarrow 2\pi^0$**

**MC $K_L \rightarrow 3\pi^0$**

**Reconstructed $K_L$ mass (MeV/c^2)**
Next steps

New photo sensor upstream

- Both-end readout of CsI crystal → new project
  - Longitudinal position with timing difference
- New 6mm□ MPPC with Silicone window
  - Low mass, UV sensitive → ~20% photo detection for 310nm

![Diagram of neutron and gamma light paths]

- 500 MeV γ
- 1 GeV neutron (downstream incident)

Efficiency

- Study on going
- ~1 order rejection!