Status on the Search for $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ with the KOTO Experiment

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On behalf of the KOTO Collaboration
$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$

- SM predicted Branching Ratio of $(3.00 \pm 0.30) \times 10^{-11}$
- Clean channel, small theoretical uncertainties (~1-2%)
- 2nd order FCNC that directly violates CP
- Origin of CP violation comes from CKM matrix
- $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ corresponds to the height of the Unitary Triangle

$V_{us} \ast V_{ud}$

$V_{cd} \ast V_{cs}$

$V_{ts} \ast V_{td}$

$V_{cs} \ast V_{cd}$

Weak eigenstates

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

CKM

Mass eigenstates

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

- SM predicted Branching Ratio of \((3.00 \pm 0.30) \times 10^{-11}\)
- Clean channel, small theoretical uncertainties (~1-2%)
- 2nd order FCNC that directly violates CP

- Good probe to search for \textit{new physics} BSM

\[ \begin{align*}
\bar{d} & \rightarrow d \\
\bar{d} & \rightarrow d \\
\bar{s} & \rightarrow d \\
\bar{s} & \rightarrow d \\
\bar{t} & \rightarrow d \\
\bar{t} & \rightarrow d \\
\bar{H}^- & \rightarrow \nu \bar{\nu} \\
\bar{H}^- & \rightarrow \nu \bar{\nu} \\
\bar{X} & \rightarrow \nu \bar{\nu} \\
\bar{X} & \rightarrow \nu \bar{\nu}
\end{align*} \]
$K^+ \rightarrow \pi^+ \bar{\nu} \bar{\nu}$ & Grossman-Nir Bound

- Charged decay equally as important (NA62) → SM BR = $(9.11 \pm 0.72) \times 10^{-11}$
- Set indirect limit on $K^0_L \rightarrow \pi^0 \bar{\nu} \bar{\nu}$ → Grossman-Nir bound
- $\text{BR}(K^0_L \rightarrow \pi^0 \bar{\nu} \bar{\nu}) < 4.4 \times \text{BR}(K^+ \rightarrow \pi^+ \bar{\nu} \bar{\nu}) \rightarrow \text{BR}(K^0_L \rightarrow \pi^0 \bar{\nu} \bar{\nu}) < 1.5 \times 10^{-9}$

E949 (2009):
BR = $(1.7 \pm 1.1) \times 10^{-10}$
BR < $3.4 \times 10^{-10}$ @ 90% CL

NA62 (2018):
BR < $11 \times 10^{-10}$ @ 90% CL
$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ Search History

- First limits on BR set in early 90s
- Best experimental limit set by KOTO in 2018

$$\text{BR}(K^0_L \rightarrow \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9} \text{ (@ 90\% CL)}$$

Experimental Setup

- Located in Tokai, Japan at J-PARC
- 30 GeV protons → stationary gold target
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- 30 GeV protons → stationary gold target
Experimental Setup

Highly collimated “pencil” beam of $K_L$, n, $\gamma$

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

Distance from target to detector = 21.5 m
Experimental Strategy

- CsI calorimeter observes 2γ from signal decay
- Difficulty → no charged particles and high efficiency required to detect all other particles
- Observe 2γ with large transverse momentum ($P_t$) and no other particles seen
KOTO Status

2015
Published results

2016-2018
Finalizing analysis

2019
New data

Accumulated P.O.T.

10^18
100
90
80
70
60
50
40
30
20
10
0

2013
First physics run

Beam Power (kW)

80
60
40
20
0

2012 Dec
2013 Dec
2014 Dec
2016 Jan
2016 Dec
2017 Dec
2018 Dec

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APS DPF 2019, Northeastern University
Results of 2015 data

\[ \text{BR}(K_L^0 \rightarrow \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9} \text{ (90\% CL)} \]


<table>
<thead>
<tr>
<th>Background source</th>
<th>Expected no. events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_L) Decays</td>
<td></td>
</tr>
<tr>
<td>(K_L \rightarrow \pi^+\pi^-\pi^0)</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>(K_L \rightarrow 2\pi^0)</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>Other (K_L) decays</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>Neutron induced</td>
<td></td>
</tr>
<tr>
<td>Hadron cluster on CsI</td>
<td>0.24 ± 0.17</td>
</tr>
<tr>
<td>Upstream (\pi^0) from NCC</td>
<td>0.04 ± 0.03</td>
</tr>
<tr>
<td>CV (\eta)</td>
<td>0.04 ± 0.02</td>
</tr>
<tr>
<td>Total background</td>
<td>0.42 ± 0.18</td>
</tr>
</tbody>
</table>

Largest background from neutrons hitting CsI

Improved previous limit (E391a)

~1 order of magnitude!
2016-2018 Improvements

- Inner Barrel (IB) installed to reduce $K_L \rightarrow 2\pi^0$ background
  - Estimated suppression x1/3

- Upgraded Data Acquisition System
  - Cluster finding in trigger → to improve DAQ efficiency

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2016-2018 Improvements

- Specific runs to study neutron induced events
  - Scatter neutrons off of Aluminum plate
  - Implemented in 2015

- Collect 8x larger sample of runs to study neutrons to improve n/γ discrimination
2016-2018 Improvements

- New cuts developed to reduce neutron background
  - Deep learning: convolutional neural network with cluster based inputs (energy, time)
  - $(1/1500)$ BG reduction with 90% signal acceptance
  - Pulse shape discrimination of n/γ by Fourier transform

\[
X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i kn}{N}}
\]
Analysis

1) Signal reconstruction
2) Normalization
3) Background estimation and reduction

● Three variables needed to calculate BR
  ○ Number of signal events
  ○ Number of $K_L^0$s generated
  ○ Signal acceptance

\[
BR(K_L^0 \to \pi^0 \nu \bar{\nu}) = \frac{N_{\text{signal}}}{N_{K_L^0} \times A_{\text{signal}}}
\]

● Single Event Sensitivity

\[
SES = \frac{1}{N_{K_L^0} \times A_{\text{signal}}}
\]
Signal Reconstruction

- Identify $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ events to calculate $N_{\text{signal}}$ to reconstruct decay vertex of the pion
- 2 clusters hit on CsI
  - Position
  - Energy
- Constraints
  - $\pi^0$ mass
  - Decay position on beamline

Reconstruct decay vertex ($Z$ position) and transverse momentum ($P_T$)

- Monte Carlo sample of $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ decay

$$\cos \theta = 1 - \frac{M_{\pi^0}^2}{2E_{\gamma_1}E_{\gamma_2}}$$

$$P_{T_{\pi^0}} = \sum_{i=1,2} E_{\text{cluster}} \frac{r_i^2}{\sqrt{r_i^2 + \Delta Z^2}}$$

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Normalization

- Calculate the number of $K_L^0$'s at the beam exit, $N_{K_L^0}$
- Normalization modes also used for
  - Measure kaon mass ($3\pi^0$)
  - Measure $z$ vertex of kaon
  - Also used for data checking and evaluating kinematic and veto cut efficiencies
  - Evaluate MC reproducibility of data
- Signal acceptance, $A_{signal}$
  - Geometric acceptance of detectors
  - Kinematic and veto efficiencies of cuts

$K_L \rightarrow 2\gamma$

$K_L \rightarrow 3\pi^0$

$K_L \rightarrow 2\pi^0$
Background Analysis

- **Charged vetos** remove events with charged particles (~80%)
- **Photon vetos** must detect other $K_L^0$ decay modes
  
  $K_L^0 \rightarrow 3\pi^0$
  $K_L^0 \rightarrow 2\pi^0$
  $K_L^0 \rightarrow \pi^+\pi^-\pi^0$

- Detailed MC studies of various background modes

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**Diagram Elements:**
- FB
- NCC
- IB
- MB
- CV
- CC04
- CC05
- CC06
- Old BHCV
- BHPV
- BHGC

**Legend:**
- Green: Photon Veto
- Orange: Neutron Counter
- Blue: Charged Particle Veto
- Red: CsI Photon Detector

**Equation:**

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

\[
K_L
\]
2016-2018 Analysis Status

- 1.5x more data than 2015 (accumulated POT ~ $3.1 \times 10^{19}$)
- SES improved x1.6 from SES = $1.3 \times 10^{-9}$ in 2015
- Background is well controlled

**Estimated SES = $8.2 \times 10^{-10}$**

<table>
<thead>
<tr>
<th>Event</th>
<th># of BG inside signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow 2\pi^0$</td>
<td>0.09±0.09</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-\pi^0$</td>
<td>0.02±0.02</td>
</tr>
<tr>
<td>Hadron cluster</td>
<td>0.07±0.13</td>
</tr>
<tr>
<td>CV-pi0</td>
<td>&lt; 0.19</td>
</tr>
<tr>
<td>CV-eta</td>
<td>0.02±0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.20±0.16</strong></td>
</tr>
</tbody>
</table>
Outlook

- Finalizing analysis → will present new results at Kaon 2019 conference in mid September
- Expect to push into the realm of new physics!

![Graph showing branching ratio limits over years with data points for various experiments including Grossman-Nir and Standard Model limits.](image-url)
Thank You

Dec '17 collaboration meeting
Supplemental
KOTO Beyond 2018

- Upgrade of detectors to further enhance background reduction

- MPPC dual ended readout of CsI crystals (2018) with Experimental run in 2019!

Attach 4080 MPPCs to 2800 crystals

6x6 mm² MPPC for small crystal

Four MPPCs for large crystal

Grouping readout of 10x10cm² region → additional readout of 256 channels
KOTO Beyond 2018

- Upgrade of detectors to further enhance background reduction

  - MPPC dual ended readout of CsI crystals (2018) with Experimental run in 2019

\[ \Delta T = T_{MPPC} - T_{PMT} \]

large \( \Delta T \) \( \Leftrightarrow \) deep \( E \) deposit

\( \Delta T \) distribution (Data)  \( \Delta T \) distribution (MC)

preliminary

n redc. eff. = 4.03%
cut at = -203 ns

1/35 neutron reduction
90\% \( \gamma \) efficiency
Signal Distribution

\[ K_{l} \rightarrow \pi^{0} \nu \bar{\nu} \text{ decay} \]

**target**

neutral pencil beam

- proton

\[ \text{Rec. } Z \text{ (mm)} \]

**w/o cuts**

\[ \text{w/o cuts} \]

\[ \text{Signal Box} \]

\[ \text{Rec. } P_{t} \]

-Assuming 2\( \gamma \) from \( \pi^{0} \)

Calculate decay vertex

\[ M^{2}(\pi^{0}) = 2E_{1}E_{2}(1 - \cos \theta) \]

Calculate \( \pi^{0} \) transverse momentum

\[ \text{Rec. } \pi^{0} P_{t} \text{ Momentum (MeV/c)} \]

**blinded region**

**blinded region**
Signal Distribution

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

```

Calculating $2\gamma$ from $\pi^0$

Calculate decay vertex

$M^2(\pi^0) = E_1 E_2(1 - \cos \theta)$

Calculate $\pi^0$ transverse momentum
```

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

w/ kinematic and veto cuts

w/ cuts

blinded region

blinded region
KOTO Detectors

- Cesium Iodide (CsI) calorimeter
- Main detector for KOTO
- 2716 channels read out by PMTs
  - 2.5 cm x 2.5 cm small crystals
  - 5 cm x 5 cm large crystals
- Timing and energy information for each crystal
- Hermetic veto detectors around decay Volume
  - ~1000 channels

Energy resolution \( (\sigma_E/E) = 0.99 \%/E_{\text{GeV}}^{1/2} \)
Timing resolution \( (\sigma_t/E) = 0.13 /E_{\text{GeV}}^{1/2} \) ns
Position resolution \( (\sigma_d/E) = \sim 2.5 /E_{\text{GeV}}^{1/2} \) mm
Discrimination methods

Shape $\chi^2$ (first run) compares observed energy deposited with the expected energy derived from MC. The sum is taken over $27 \times 27$ crystals around the cluster center.

$\chi^2 = \frac{1}{N} \sum \left( \frac{e_i}{E_{inc}} - \mu \right)^2$

- $E_{inc}$: measured photon energy
- $e_i$: measured deposit energy in $i$th crystal in a cluster
- $\mu$: expected mean $e/E$
- $\sigma$: expected RMS of $e/E$

(1/300) BG reduction with 80% signal acceptance
Discrimination methods

Cluster Shape Discrimination (CSD) uses energy and timing information from the CsI as inputs into a Neural Net:

- (1/1500) BG reduction with 90% signal acceptance

- Main inputs: Energy $\chi^2$, Cluster $E_{\text{difference}}$, timing $\chi^2$, Cluster COE, Cluster RMS, crystal energy probability...

![Energy distribution](image1)

![Timing distribution](image2)

![Neural Net outcome of shape cut](image3)
Discrimination methods

Pulse Shape Discrimination (PSD) cut uses waveform information to discriminate photon and hadronic showers

- Fitted waveforms with asymmetric Gaussian, obtained templates, and calculated likelihood ratio from fit parameters taken from control and photon samples
- Difference in the tail of hadronic showers corresponds to a larger $a$

\[
A(t) = |A|e^{\frac{(t-t_0)^2}{2\sigma(t)^2}}
\]

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

Fitted waveform with asymmetric Gaussian
Discrimination methods

Pulse Shape Discrimination (PSD) cut uses waveform information to discriminate photon and hadronic showers

- Fitted waveforms with asymmetric Gaussian, obtained templates, and calculated likelihood ratio from fit parameters taken from control and photon samples

- Difference in the tail of hadronic showers corresponds to a larger (a)

- (1/10) BG reduction with 90% signal acceptance
Signal Region

\( K_L \rightarrow \pi^+\pi^-\pi^0 \) MC (Loose cut condition)

Slope to suppress \( K_L \rightarrow \pi^+\pi^-\pi^0 \) BG

\[ Z = 3000 \quad Z = 4700 \]

\( A_{\text{sig}} \quad N_{\text{BG}} \)

-15%  -0.04

\( \ast \) same as 2013 run

+3%  +0.04

+23%  +0.30

\( Z = 5000 \)
$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ Feynman Diagrams
DAQ Logic Signal Flow

1. **Trigger & no veto**
   - **>100 clocks since previous L1preA**
     - Yes: **Room in L2 memory**
     - No: **L1 Raw**

2. **Room in L2 buffers**
   - Yes: **L1 pre Accept**
     - Yes: **L1 Accept 5 clocks**
     - No: **L1 Reject**
   - No: **L2 buffer deadtime**

3. **L2 buffer deadtime**
   - Yes: **L2 Reject**
   - No: **L2 memory deadtime**

4. **L2 memory deadtime**
   - Yes: **CDT inhibit deadtime**
     - Yes: **L2 Reject**
     - No: **CDT deadtime**
   - No: **1, 3, 5, ≥ 7**

5. **Number of Clusters**
   - 4 or 6: **L1 Accept 3 clocks**
   - 2: **L1 Accept 5 clocks**

6. **Transmit L1 Pre-Accept**
   - **Physics Trigger**
   - CoE and CDT NOT applied

7. **Send to L3**

8. **Send to L2**

9. **Pass CDT**
   - Yes: **Send to L2**
   - No: **L1 Reject**

10. **L1 Accept 5 clocks**
    - **Overlap with L1A (12 clocks)**
    - **L1 Accept**
      - Yes: **Send to L2**
      - No: **L1 Reject**
    - **L1 pre Accept**
      - Yes: **Send to L2**
      - No: **L1 Reject**

11. **Pass CoE**
    - Yes: **Send to L3**
    - No: **L2 Reject**

---

**Normalization Minimum Bias Laser LED**

**Deadtime**

**Overlap with L1A**

**Reject**

**Accept**
2013 Data Analysis

- 2013 data analysis revealed largest contribution to background is neutrons hitting detector material
  \[ BR(K^0_L \rightarrow \pi^0 \nu \bar{\nu}) < 5.1 \times 10^{-8} \text{ @ 90\% CL} \]

- New detector changes to reduce neutron background
  - Improved surface alignment of collimators; BPM (Beam Profile Monitor)
  - Vacuum window replaced
  - Specific experimental runs with aluminum target to study neutron background

- Beam Hole Charge Veto
  - Suppress \( \pi^+ \pi^- \pi^0 \)

- Beam Hole Guard Counter
  - Tag photons escaping near edge of beam hole