Status of $K_L \rightarrow \pi^0 \nu \nu$ Search

Chieh Lin  [The University of Chicago]
DISCRETE 2021
New Physics in Golden Mode $K_L \rightarrow \pi^0 \nu \nu$

Clean & Rare $\implies$ Sensitive to New Physics:

$$BR(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$$

Grossmann-Nir bound (Model independent)

$$BR(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) \leq 4.3 \times BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$$

$$\leq 6.3 \times 10^{-10} \quad (68\% \ C.L.)$$

$\implies$ Not applicable to $K_L \rightarrow \pi^0 X$, where $m_{X^0} \approx m_{\pi^0}$, because this region is not experimentally examined.
The KOTO Experiment

- **Signal Requirement**
  - $2\gamma$ from $\pi^0$ on calorimeter
  - Missing $P_T$ due to neutrinos.
  - Nothing else detected

- **Blind Analysis**
  - The distribution in the signal box is inaccessible.
**K_{L\to\pi^0\nu\nu} Result Based on 2016 - 2018 Data**

- **SES = (7.20 ± 0.05^{stat}_{} ± 0.66^{syst}_{} ) \times 10^{-10}**
- **BR(K_{L\to\pi^0\nu\nu}) < 4.9 \times 10^{-9} (90\% \ C.L.)**
- Based on three observed candidate events.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{L\to\pi^0}$</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>$K_{L\to2\gamma}$ (beam halo)</td>
<td>0.26 ± 0.07^{a}</td>
</tr>
<tr>
<td>Other $K_{L}$ decays</td>
<td>0.005 ± 0.005</td>
</tr>
<tr>
<td>$K^{\pm}$</td>
<td>0.87 ± 0.25^{a}</td>
</tr>
<tr>
<td>Neutron</td>
<td>0.017 ± 0.002</td>
</tr>
<tr>
<td>CV $\eta$</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>Upstream $\pi^0$</td>
<td>0.03 ± 0.03</td>
</tr>
<tr>
<td>Total</td>
<td>1.22 ± 0.26</td>
</tr>
</tbody>
</table>

^{a}Background sources studied after looking inside the blind region.

[Expected vs. Observed Table]

- Observed: 439, Expected: 436.79 ± 3.83
- BR(K_{L\to\pi^0\nu\nu}) < 4.9 \times 10^{-9} (90\% \ C.L.)

[PRL 126, 121801 (2021)]
Primary Background: $K^+$ Decay

$K^+ \rightarrow \pi^0 e^+ \nu$ background can be threatening.

- $\pi^0$ kinematics is similar with signal.
- Inefficiency of backward $e^+$ is large.
K⁺ Flux Measurement at 2020 Special Run

Reconstruct K⁺→π⁰π⁺ (BR ~ 20%) for K⁺ flux measurement.

K⁺ / K⁻ flux ratio = (2.6 ± 0.1) x 10⁻⁵.
2nd Largest Background: Halo $K_L$ Decay

- Downstream off-axis $K_L \rightarrow 2\gamma$ decay can be threatening.
  - $\pi^0$ mass assumption leads to the upstream shift.
  - The off-axis decay is misinterpreted as large $P_T$.

Elastic scattering at collimator or photon absorber.
2nd Largest BGL: Halo $K_L \rightarrow 2\gamma$ Background Level

$R_{COE} = \frac{\sqrt{\left( \sum E_i x_i \right)^2 + \left( \sum E_i y_i \right)^2}}{\sum E_i}$

After the correction through $R_{COE}$, halo $K_L \rightarrow 2\gamma$ BGL is predicted to be $(0.26 \pm 0.07)$. 

![Graph showing data and MC for COE radius and $Z_{vtx}$ with halo kaon highlighted.](image)
**$K_L \rightarrow \pi^0 X$ Interpretation**

- $X$ with mass range of 0.1 — 280 MeV.
- $X$ can decay into $e^+ e^-$ pair with lifetime range 0.1 — 5 ns

\[ SES = 1/(N_{K_L} \times A_{\text{sig}}) \]

Estimated by MC.

**MC predictions**

**X mass = 0.1 MeV**

**X mass = 280 MeV**
\( K \rightarrow \pi^0 X \) Branching Ratio Result

\[ \text{BR}(K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \text{invisible}) < 4.4 \times 10^{-9} \ (90\% \ C.L.) \]

KOTO further examines the \( M_\pi \) region.

\[ \text{BR}(K^0_L \rightarrow \pi^0 X, M_X = M_\pi^0) < 3.7 \times 10^{-9} \]

(Preliminary) (90\% C.L.)
KOTO Next Step: K+ Background Suppression

- Upstream charged veto (UCV) counter was installed in 2021.
- Electron beam test showed 5% inefficiency.
  - BGL(K+ decay) $\sim 20 \rightarrow 1$ at SM.
KOTO Next Step: Halo $K_L$ Background Suppression

PDF(shower shape, incident angle)

COE

$z$-axis

$\pi$

PDF(on-axis)

PDF(off-axis)

BG rejection: 85%

Signal efficiency: 90%

Likelihood Ratio

LR = \frac{PDF(on-axis)}{PDF(on-axis) + PDF(off-axis)}

CUT
KOTO Data Collection History and Future

- 2019 - 2020 w/o UCV data:
  Establish NN-based kinematic cut against K⁺ background.
- 2021 w/ UCV
  Examine UCV performance.
- 2022 -
  Continuously collect data with beam power 60 - 100kW

POT: proton on target

* POT: proton on target
Summary

- $K_L \rightarrow \pi^0 \nu\nu$ analysis result based on 2016 - 2018 data was released in March 2021.  
  ⇒ Collimator-scattered $K^+$ and $K_L$ particles are found to be threatening.

- An interpretation of $K_L \rightarrow \pi^0 X$ (where $X$ is steady or decays to $e^+e^-$ pair) is performed:  
  In particular, $\text{BR}(K_L \rightarrow \pi^0 X, X \text{ is steady and } M_X=M_{\pi}) < 3.7 \times 10^{-9}$ (90% C.L.) [preliminary].

- An upstream plastic scintillator is implemented to suppress $K^+$ background.  
  A shower shape algorithm is established to suppress halo $K_L$ particles.

- Data collected during 2019 - 2021 is about doubled of the 2016 - 2018 data set and its analysis is now ongoing.
Supplement
K+ Background Level

\[ K^+ \rightarrow \pi^+ e^+ \nu \] Background Level

![Graph showing K+ to pi+ e+ nu background level with data points and error bars.](image-url)