The KOTO Experiment at the J-PARC

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LEPP Journal Club @Cornell
K0 at TOkai(KOTO) for the rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$

- ~65 members from 5 countries, 16 institutions

KEK
Kyoto
NDA
Osaka
Saga
Yamagata
Arizona State
Chicago
Michigan
JINR
National Taiwan
Cheju
Chonbuk
Kyungpook
Pusan National
Seoul
Outline

• Physics
• Strategy
• The pilot E391a
• How do we do it
• Timeline and summary
Why $K_L \rightarrow \pi^0 \nu \bar{\nu}$

- Flavor changing neutral current at the loop level

- A direct CP violation process

\[ A(K_2 \rightarrow \pi^0 \nu \bar{\nu}) \propto V_{td}^* V_{ts} - V_{ts}^* V_{td} \propto 2i \eta \]

$K_1$ (or $K_{\text{even}}$) contribution negligible
Small Theoretical Uncertainty

- The hadronic matrix element is substituted with known measurement.
- Uncertainty in the Standard Model prediction almost entirely comes from the CKM parameters, the top and W mass.

\[
Br(K^0_L \rightarrow \pi^0\nu\bar{\nu}) = 6.87 \times 10^{-4} \times Br(K^+ \rightarrow \pi^0e^+\nu) \times A^4\lambda^8\eta^2X^2(x_t) \\
= (2.49 \pm 0.39) \times 10^{-11}
\]
Beyond standard model

• Large room for new physics with new heavy particles remains with the current branching ratio limits

http://www.lnf.infn.it/wg/vus/content/Krare.html
A short history

• Earlier searches using $\pi^0$ decaying into 2 $\gamma$’s were crippled by limited veto abilities.

• A more sensitive search used the $\pi^0$ Dalitz decay. But acceptance is greatly sacrificed.
The Basic Strategy

- Pencil beam
- Hermetic veto
- Reconstruction of $\pi^0$ vertex and its transverse momentum assuming $\pi^0$ mass
- Daunting task to sort out two photons from one trillion events -> Step by Step
Pilot E391a at KEK(2001-2005)

- Decay region in high vacuum($10^{-7}$ Torr)
MC $K_L \rightarrow \pi^0 \nu \bar{\nu}$ after Reconstruction

- Signal Simulation

Acceptance 1%, largely due to shower shape cut.

Kaon beam parameters were checked using other neutral decay modes

Momentum from $K_L \rightarrow 3 \pi^0$
E391a Background Simulation-Neutron Related

Neutron interactions with detector close to the beam are the E391a main background sources.

<table>
<thead>
<tr>
<th>BG</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC02 ‘pi0’</td>
<td>0.6+/−0.4</td>
</tr>
<tr>
<td>CV-eta</td>
<td>0.2+/−0.1</td>
</tr>
<tr>
<td>CV-pi0</td>
<td>&lt;0.3</td>
</tr>
</tbody>
</table>

At a sensitivity of 1.1×10⁻⁸
E391a Background Simulation: $K_L \rightarrow 2 \pi^0$

- Soft photons are lost in MB and energetic photons punch through $16X_0$ of CsI

E391a $K_L \rightarrow 2 \pi^0$ background expected 0.024$^{+/-}$0.018

Scale not normalized
Pilot E391a Result

- Data plot of blind analysis
Pilot E391a result

- Data plot of blind analysis, open the box
- $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8} (90\% \text{ CL})$

- Main background: halo neutron interaction
How do we improve from E391a

• More $K_L$, less halo neutron $\rightarrow$ Beam
• Background and acceptance $\rightarrow$ Calorimeter and electronics
• Background $\rightarrow$ Main veto detectors
Beam
The Primary Beam

- Proton intensity is improved by a factor of ~100
- Slow extraction from the main ring for KOTO
The Beamline Design

- A long beamline with large extraction angle
  -> to suppress hyprons, $K_s$, to have soft Kaon momentum with higher energy primary beam

Halo neutron produced by scattering off the inner surface of collimators -> inner surface not facing the target
The downstream collimator was further optimized to reduce the multiple scattering and accommodate the lead absorber
Beamline Simulation

- Neutron profile expected
Picture of the Beamline
Beam Survey of Halo Neutron

- Halo neutron measurement with two pieces of heavy scintillators
  - look for hit in the downstream one
To Further Reduce Neutron Background

Move CC02 upstream and make it fully active.

The new beamline and this configuration of CC02 and CV reduce the halo neutron to $K_L$ ratio by a factor of $\sim 230$. 

KOTO

Beam

E391a

Front

Rear

6mm

outer

3mm

Inner

CsI

7x7x30cm

CsI

2.5x2.5x50cm

signal region
Comparison of halo neutron momentum

E391a at KEK-PS

KOTO at J-PARC

MC study of η particle production

The 10 GeV momentum cut off limits high energy Λ production at CC02
Detector Upgrades

![Diagram of detector upgrades](image)
Calorimeter
KTeV CsI calorimeter

E391 CsI crystal 7cmx7cmx30cm \(16X_0\)

KTeV crystal geometry

Feb, 2011
Longer CsI Reduces Shower Leakage

Better energy resolution suppresses the background caused by neutron interaction with veto counters.

Energy in CsI as a fraction of incident photon energy

The halo neutron background is expected to be 0.2 for KOTO. Main background become intrinsic $K_L$ decay($K_L\rightarrow 2\pi^0$).
Effect on $K_L \rightarrow 2\,\pi^0$ background (punchthrough)

- Calorimeter acts as a veto detector

- Main mechanism for $K_L \rightarrow 2\,\pi^0$ background becomes ‘even-paring’ events with two photon missing in veto detectors instead of CsI punch through.
Calorimeter Readout
KTeV Calorimeter → KOTO Calorimeter (Chicago)

- New in KOTO: high rate, different energy range, vacuum, higher timing requirement, vacuum
- CW base → low power
- Differential outputs to the 125MHz waveform digitizer
The Gaussian Filter in the FADC

- Challenge of sampling 3000 fast rising/falling pulses. **Cost and the amount of storage.**
- Solution: shape the CsI pulse into a quasi-Gaussian pulse.

![Filter circuit diagram](image-url)

CsI pulse (inverted). Yellow: filtered
Timing Measurement with an ADC

- Full pulse sampling allows fitting to determine the time of the pulse
- Timing measurement is important for veto and reducing acceptance loss. A good timing measurement also have the potential to find the angle of the photon. The angle measurement suppresses a large class of background.

Smaller pulses have irregular shapes

Timing resolution ~110ps at E=100MeV
Two Pulse Separation

200MeV + 40MeV

2MeV + 10MeV
Readout and Architecture

- Fully pipelined system with no delay cable
- With 48 samples for a pulse, the FADC board can send out data at a trigger rate of >100kHz. Data throughput: 20GByte/second
- Multi leveled trigger system
Major veto detectors
Catching photons down the beam hole

• Challenge: efficient for photon and inefficient for neutron
• Readout fast pulses: 500MHz FADC board (Chicago)
• Energetic photons go down the hole
KOTO Main Barrel (MB)

- With the improvement in the beam and Calorimeter, the main background comes from $K_L \rightarrow 2\pi^0$ with missing photons.
- Adding another $5X_0$ to the $14X_0$ E391a MB reduces $K_L \rightarrow 2\pi^0$ background by a factor of 2.
How can we go further?

- MB Inefficiency Mechanism MC Study

Low energy sampling effect dominate

For perpendicularly incident photons, $19X_0$ isn’t enough for punch though.

Not many such photons in MB, but many such photons in CsI. This explains why $E391a K_L$-$2\pi^0$ background comes from ‘punch through’.
MB II (in plan)

- The inefficiency for photons with energy <30MeV is caused by the sampling effect in the Pb/scintillator sandwich structure.
- Using CsI in front of Pb/scintillator MB can further reduce the $K_L \rightarrow 2\pi^0$ background by 40%

3cm of CsI in front of CsI
Background and Sensitivity

<table>
<thead>
<tr>
<th></th>
<th>J-PARC KOTO</th>
<th>KEK-E391a</th>
<th>improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>KL yield/spill</td>
<td>8.1x10^6</td>
<td>3.3x10^5</td>
<td>x30/sec</td>
</tr>
<tr>
<td>Run time</td>
<td>12 months</td>
<td>2 months</td>
<td>x6</td>
</tr>
<tr>
<td>Decay prob.</td>
<td>3.6%</td>
<td>2.1%</td>
<td>x2</td>
</tr>
<tr>
<td>Acceptance</td>
<td>4.7%</td>
<td>1%</td>
<td>x3.6</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.8x10^-11</td>
<td>1.1x10^-8</td>
<td>x1300</td>
</tr>
</tbody>
</table>

With no CsI lining MB

<table>
<thead>
<tr>
<th>Background source</th>
<th>#evts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0$</td>
<td>1.8</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-\pi^0$</td>
<td>0.46</td>
</tr>
<tr>
<td>n + residual gas</td>
<td>0.04</td>
</tr>
<tr>
<td>n + upstream veto</td>
<td>0.13</td>
</tr>
<tr>
<td>accidental coincidence</td>
<td>0.10</td>
</tr>
<tr>
<td>sum</td>
<td>2.5</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0\nu\bar{\nu}$ signal</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Timeline

• Beamline construction done in 2009
• Engineering run in the fall of 2010
Engineering Run (10/2010-11/2010)

- With half of the calorimeter and 3-5kW primary beam
- Spectrometer in front of the calorimeter ← calibration with momentum-measured electrons
Results from Engineering Run

candidate of \( K_L \rightarrow 3\pi^0 \)

spectrometer in front of the calorimeter
← calibration with momentum-measured electrons
Timeline

- Beamline construction done in 2009
- Engineering run in the fall of 2010
- Calorimeter construction done in March 2011
- Full detector to be completed by the end 2011
- Physics run start in 2012 (with 30 kW beam)
Report on 03/11/2011 Earthquake

Need Electricity!
Summary

• The KOTO experiment aims to discover the SM $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events at Step 1
• Breach into the new physics from 2012
• Step 2(100 Golden events) after a good understanding of step 1
  go back to smaller angle
  longer decay volume->longer MB
bigger calorimeter
retool the beamline
Backup
Beam Survey

With 1-3kW beam
At the endcap
Background from $K_L$ Charged Mode Decays

- Main contribution comes from $K\pi\pi$ decay. $K\pi\pi$(e-e+nu, bigger inefficiency) background is negligible because extra particles going into the calorimeter.

Inefficiency verified with CV prototype.
Fusion

- K->2pi0 fusion background is about 10% of total background
- To reject fusion events, E391a suffered ~60% acceptance loss. In KOTO, the fusion background is reduced with a small acceptance loss.

5cm distance between two photon to identify fusion using KOTO calorimeter; 15cm for E391a
## Beam Parameter Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>J-PARC KOTO</th>
<th>KEK-E391a</th>
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</thead>
<tbody>
<tr>
<td>Primary proton energy</td>
<td>30 GeV</td>
<td>12 GeV</td>
</tr>
<tr>
<td>Proton intensity (/spill)</td>
<td>$2 \times 10^{14}$</td>
<td>$2.5 \times 10^{12}$</td>
</tr>
<tr>
<td>Spill-length/repetition</td>
<td>0.7s / 3.3s</td>
<td>2s / 4s</td>
</tr>
<tr>
<td>Production target</td>
<td>Nickel disks</td>
<td>Pt rod</td>
</tr>
<tr>
<td>Extraction angle</td>
<td>16 deg.</td>
<td>4 deg.</td>
</tr>
<tr>
<td>KL yield (/spill)</td>
<td>$8.1 \times 10^6$</td>
<td>$3.3 \times 10^5$</td>
</tr>
<tr>
<td>Average $P_{KL}$</td>
<td>2.1 GeV/c</td>
<td>2.6 GeV/c</td>
</tr>
<tr>
<td>$n/K_L$ ratio</td>
<td>6.5</td>
<td>45</td>
</tr>
<tr>
<td>Halo neutron/$K_L$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$3.3 \times 10^{-1}$</td>
</tr>
</tbody>
</table>
CKM matrix and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

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

CKM matrix connects weak eigenstates and mass eigenstates

$$
V_{ub}V_{ud} + V_{cb}V_{cd} + V_{tb}V_{td} = 0
$$

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

$$
\text{Br}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})_{SM} = \frac{\kappa L}{X} \left| \text{Im}(V_{ts}^*V_{td}) \right|^2
$$

$$
= (2.49 \pm 0.39) \times 10^{-11}
$$

$\kappa$ is related to the isospin breaking correction and $X$ is a function of $m_t$ and $\alpha_s$.

(F. Mescia and C. Smith, PRD76, 074017(2007) )