Status and Prospects of the KOTO Experiment

Yu-Chen Tung (Univ. of Chicago) for the KOTO collaboration
Who are We?

- We have around 50 collaborators from 17 institutes
  - Arizona, Chicago, Chonbuk, Jeju, JINR, KEK, Kyoto, Kyungpook, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga, Seoul, & Yamagata

KOTO Collaboration
Where are We?

JPARC

Hadron Hall

Japan Atomic Energy Agency
What are We Measuring?

$K_L \to \pi^0 \nu \bar{\nu}$ decay
- direct CP violating process
- FCNC via loop diagram
- branching ratio from SM: $2.4 \times 10^{-11}$ with 2% uncertainty
- excellent mode to test SM and beyond
Signal Detection

- Target
- Proton 30 GeV
- Collimator & Magnet
- Hermetic Detector
- γ in CsI + 0 in others
- High Pt + Fiducial Z

Proton 30 GeV → γγ
νν

\[ K_L \rightarrow \pi^0 \nu \nu \]
Measurement of $\kappa_L^0$ flux at the J-PARC neutral-kaon beam line


Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 664, Issue 1, 1 February 2012, Pages 264–271
Experimental study of the decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

Current Limit $< 2.6 \times 10^{-8}$

(E391a Collaboration)
First Physics Run (May 2013)

10^{-13} \quad 10^{-12} \quad 10^{-11} \quad 10^{-10} \quad 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6}

E391a

Delay by radiation accident

Grossman-Nir limit

SM Prediction

Integrated N of P.O.T = (sec * 9.24 \times 10^9)

(100 hours)

8.0 \times 10^{18} \text{ P.O.T} (original goal)

1.6 \times 10^{18} \text{ P.O.T} (actual)

First Physics Run (100hrs @ 25kW)
Where We Are & Where We Go

The data-taking has resumed since April, 2015

E391a
S.E.S. = 1.11x10^-8

KOTO
S.E.S. = 1.29x10^-8 with only 100hrs data

Grossman-Nir limit

SM Prediction

The data-taking has resumed since April, 2015
First Physics Run (May 2013)

- Unbiased blind analysis
- Expected $0.36 \pm 0.16$ BKGD events

<table>
<thead>
<tr>
<th>BG Source</th>
<th># of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream</td>
<td>$0.18 \pm 0.15$</td>
</tr>
<tr>
<td>Low Pt</td>
<td>$0.11 \pm 0.04$</td>
</tr>
<tr>
<td>Upstream</td>
<td>$0.06 \pm 0.06$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$0.36 \pm 0.16$</td>
</tr>
</tbody>
</table>
First Physics Run (May 2013)

- Unbiased blind analysis
- Expected 0.36±0.16 BKGD events
- One event in the signal box

<table>
<thead>
<tr>
<th>BG Source</th>
<th># of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream</td>
<td>0.18±0.15</td>
</tr>
<tr>
<td>Low Pt</td>
<td>0.11±0.04</td>
</tr>
<tr>
<td>Upstream</td>
<td>0.06±0.06</td>
</tr>
<tr>
<td>Total</td>
<td>0.36±0.16</td>
</tr>
</tbody>
</table>
Where We Are & Where We Go

To go below, We need to:
- overcome neutron background
- add more detectors
- reduce accidental rate
### 2013 to 2015

<table>
<thead>
<tr>
<th>BG Source</th>
<th># of Events</th>
<th>Possible Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>0.06±0.06</td>
<td>Halo neutron interacted with upstream detector: n+A→π⁰+X</td>
</tr>
<tr>
<td>Low Pt</td>
<td>0.11±0.04</td>
<td>Kₐ→π⁰π⁺π⁻ with two undetected charged pions in beam pipe</td>
</tr>
<tr>
<td>Downstream</td>
<td>0.18±0.15</td>
<td>Neutron scattered in CsI and produced two clusters</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.36±0.16</strong></td>
<td><strong>Neutron scattered in CsI and produced two clusters</strong></td>
</tr>
</tbody>
</table>
2013 to 2015

Thiner beam window to reduce neutron interaction

Better beam profile monitor for beam alignment.

<table>
<thead>
<tr>
<th>BG Source</th>
<th># of Events</th>
<th>Possible Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>0.06±0.06</td>
<td><em>Halo neutron interacted with upstream detector: n+A→π⁰+X</em></td>
</tr>
<tr>
<td>Low Pt</td>
<td>0.11±0.04</td>
<td><em>K_L→π⁰π⁺π⁻ with two undetected charged pions in beam pipe</em></td>
</tr>
<tr>
<td>Downstream</td>
<td>0.18±0.15</td>
<td><em>Neutron scattered in CsI and produced two clusters</em></td>
</tr>
<tr>
<td>Total</td>
<td>0.36±0.16</td>
<td></td>
</tr>
</tbody>
</table>
**BG Source** | **# of Events** | **Possible Mechanism**
--- | --- | ---
**Upstream** | 0.06±0.06 | Halo neutron interacted with upstream detector: $n+A \rightarrow \pi^0 + \chi$
**Low Pt** | 0.11±0.04 | $K_L \rightarrow \pi^0 \pi^+ \pi^-$ with two undetected charged pions in beam pipe
**Downstream** | 0.18±0.15 | Neutron scattered in CsI and produced two clusters
**Total** | 0.36±0.16 |
New charged veto detector along beam pipe (BPCV)

### Possible Mechanisms

<table>
<thead>
<tr>
<th>BG Source</th>
<th># of Events</th>
<th>Possible Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>0.06±0.06</td>
<td>Halo neutron interacted with upstream detector: n+A→π⁰+X</td>
</tr>
<tr>
<td>Low Pt</td>
<td>0.11±0.04</td>
<td>KL→π⁰π⁺π⁻ with two undetected charged pions in beam pipe</td>
</tr>
<tr>
<td>Downstream</td>
<td>0.18±0.15</td>
<td>Neutron scattered in CsI and produced two clusters</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.36±0.16</strong></td>
<td></td>
</tr>
</tbody>
</table>
2013 to 2015

<table>
<thead>
<tr>
<th>BG Source</th>
<th># of Events</th>
<th>Possible Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upstream</strong></td>
<td>0.06±0.06</td>
<td>Halo neutron interacted with upstream detector: $n+A \rightarrow \pi^0 + \chi$</td>
</tr>
<tr>
<td><strong>Low Pt</strong></td>
<td>0.11±0.04</td>
<td>$K_L \rightarrow \pi^0 \pi^+ \pi^-$ with two undetected charged pions in beam pipe</td>
</tr>
<tr>
<td><strong>Downstream</strong></td>
<td>0.18±0.15</td>
<td>Neutron scattered in CsI and produced two clusters</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.36±0.16</td>
<td></td>
</tr>
</tbody>
</table>
### BG Source

<table>
<thead>
<tr>
<th>BG Source</th>
<th># of Events</th>
<th>Possible Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>0.06±0.06</td>
<td>Halo neutron interacted with upstream detector: n+A→π⁰+X</td>
</tr>
<tr>
<td>Low Pt</td>
<td>0.11±0.04</td>
<td>K_L→π⁰π⁺π⁻ with two undetected charged pions in beam pipe</td>
</tr>
<tr>
<td>Downstream</td>
<td>0.18±0.15</td>
<td>Neutron scattered in CsI and produced two clusters</td>
</tr>
<tr>
<td>Total</td>
<td>0.36±0.16</td>
<td></td>
</tr>
</tbody>
</table>

2013 to 2015

Aluminum target

- Collect more neutron events
- Cluster shape to identify γ/n
Accidental Loss: Beam Line

Accidental loss / 2 after
- beam tuning
- add shielding

Acceptance loss of Each Detector

Data vs. MC

Before beam tuning (2015)
After beam tuning (2015)
May 2013

MB Counting Rate
Accidental Loss: Detector

New Beam Hole Charged Veto (BHCV)
- 30x30cm x 3 wire chambers
- efficiency > 99.5%
- Rate > 100kH/cm²
- accidental loss: 30% → 15%

CF₄:n-Pentane = 55:45
Accidental Loss: Analysis

Full waveform analysis
- better timing determination
- signal/accidental discrimination

16ch x 14bits 125MHz FADC

![Graph showing differential energy vs FADC sample]
Current Limit by E391a is beyond the Map & KOTO reached the same sensitivity with only 100hrs of data
Now targeting Grossman-Nir limit with data collected in 2015
Full Completion of Detector

14X₀ → 14X₀ + 5X₀
S/Nx1.8

25 layers of Pb/Scinti sandwich
Reach SM sensitivity in 2018
- Larger detector (15m long)
- Higher beam power (>400kW)
- 100 SM events with S/N~5
Summary


Step-1 target: reach $0(10^{-11})$ S.E.S. in 2018

Step-2: 100 SM events