Status of the KOTO experiment
(search for $K_L \rightarrow \pi^0 \nu \bar{\nu}$)

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The experiment brings together over 50 collaborators from 16 different institutions.

August '16 collaboration meeting
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Aim of KOTO

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Motivation

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

- Directly breaks CPV
- Permits probing for New Physics (NP) beyond the standard model
- Process occurs via a flavor changing neutral current (FCNC)
- Validate Standard Model or discover new physics

\[ CP' \quad CP_x \]
\[ K_L \rightarrow \pi^0 \nu \nu \]
Dominant uncertainties for SM BRs are from CKM matrix elements.

Non agreement between B and K decays indicates new physics and may provide evidence for NP.

Intrinsic theory uncertainties ~ few percent.

BR is proportional to CKM height.

Small theoretical uncertainty ~2%.

\[ \text{BR} (K^+ \rightarrow \pi^+ \nu \nu) = (9.11 \pm 0.72) \times 10^{-11} \ (\text{Buras et al. 2015}) \]

\[ \text{BR} (K_L \rightarrow \pi^0 \nu \nu) = (3.00 \pm 0.30) \times 10^{-11} \ (\text{Buras et al. 2015}) \]

Fig. Unitary triangle

Non agreement between B and K decays indicates new physics.
New physics via $K_L \rightarrow \pi\nu\nu$ decays

Strong correlations seen in two-branch structure between Beyond Standard Model (BSM) predictions with left-hand/right-hand exclusive FCNC

No correlations in the $K \rightarrow \pi\nu\nu$ plane for models with this constraint

Fig. Predicted correlations between $BR(K_L \rightarrow \pi^0\nu\nu)$ and $BR(K_L \rightarrow \pi^+\nu\nu)$ for various BSM.
Model predictions and measurements

BNL: E949 observed 2 clean events for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ~ BR (1.73 x 10^{-10})

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 $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73 \pm 1.15) \times 10^{-10}$ consistent with the standard model prediction.

Fig. History $K_L \rightarrow \pi \nu \nu$ search

LHT: Littlest Higgs (T-parity)
MFV: Minimum Flavor Violation
RSc: Randall-Sundrum

Fig. Predicted correlations between $\mathcal{BR}(K_L \rightarrow \pi^0 \nu \nu)$ and $\mathcal{BR}(K_L \rightarrow \pi^+ \nu \bar{\nu})$ for various BSM.
Goals of KOTO

Measure 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)
Measuring $K_L \rightarrow \pi^0 \nu \nu$

~30 billion kaons
Improvements in detectors and data processing were instrumental in advancement.

E391a was impeded by limited veto capabilities and lower beam power (~12 GeV).

**Figure 1.3:** History of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ search.

A green point shows the first study performed by Littenberg. Blue (Red) points in the figure show results of the analysis using a $\pi^0 \rightarrow e^+ e^-$ decay. A green line shows the GN limit. A pink line shows the prediction in the Standard Model.

**Figure 3.6:** E391a detection system.

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**3.2 Detectors**

**3.2.1 Overview**

The E391a detection system was located at the end of the beamline. The detector subsystems were cylindrically arranged around the beam axis, and most of them were placed inside a large vacuum vessel, as shown in Fig. 3.6. From here on, the origin of the coordinate system is defined to be at the upstream end of the E391a detector, as shown in Fig. 3.6. This position was approximately 12 m from the production target.

**3.2.2 CsI calorimeter**

The energy and hit position of the two photons were measured by using an electromagnetic calorimeter placed at the downstream end of the decay region. The calorimeter was made of 576 undoped CsI crystals and assembled in a support cylinder with an inner diameter of 1.9 m, as shown in Fig. 3.7. A collar counter (CC03) was installed inside of the calorimeter with a 12 cm $	imes$ 12 cm hole, which is described later. The CsI calorimeter was placed at $z = 614.8$ cm. Most of the crystals had a square shape, with the exception of crystals located at the outer edge. In order to fill the gap at the periphery of the cylinder between the square-shaped crystals and the support structure, specially shaped CsI crystals (Edge CsI) and lead-scintillator sandwich counter (Sandwich module) were placed at the outer edge of the main CsI crystals.

CsI crystals

Two different sizes of crystals were used in the array: 496 crystals, called “Main CsI”, had a dimension of $7 \text{ cm} \times 7 \text{ cm} \times 30 \text{ cm} = 16 \times X_0$ and 24 crystals, called “KTeV CsI”, had a dimension of $5 \text{ cm} \times 5 \text{ cm} \times 50 \text{ cm} = 27 \times X_0$. Each Main CsI crystal was wrapped with a $100 \mu \text{m}$ thick Teflon sheet and then wrapped with a $20 \mu \text{m}$ thick Aluminized mylar, in order to isolate each crystal optically and to improve the light collection. The Main CsI crystal yielded typically 15 photoelectrons per energy deposition of 1.

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Precursor to KOTO

Dedicated pilot search was the KEK E391a collaboration

- Indirect branching ratio limit \( (K_L \rightarrow \pi^0 \nu\nu) < 1.5 \times 10^{-9} \) set by BNL E787/949 using isospin symmetry

- Set upper limit \( BR(K_L \rightarrow \pi^0 \nu\nu) < 2.6 \times 10^{-8} \) (90% confidence)

- Limits of the detector were identified motivating next steps

- Having only upper limits determined drives the experiment and indicates there is still more to be explored

KOTO detector is specifically designed to measure the CP-violating \( K_L \rightarrow \pi^0 \nu\nu \) rare decay
J-PARC facility

“$K^0$ at TOkai”

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

- Various research projects
  - roughly 20 hrs of travel from Ann Arbor

![Figure 2.1: A bird's-eye view of the entire J-PARC facility. This figure is obtained from [5].](http://ptep.oxfordjournals.org/)

### Table 2.1: A list of parameters of J-PARC accelerator facilities.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Ion Species</th>
<th>Repetition Cycle</th>
<th>Extraction Beam Energy</th>
<th>Circumference</th>
<th>Beam Cycle</th>
<th>Extraction Beam Energy</th>
<th>Achieved Beam Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac</td>
<td>Negative hydrogen ions</td>
<td>25Hz</td>
<td>400MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCS</td>
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<td>25Hz</td>
<td></td>
<td>348.333 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MR</td>
<td></td>
<td></td>
<td></td>
<td>1567.5 m</td>
<td>2.56 s (FX), 5.52 s, 6.0 s (SX)</td>
<td>43 kW (SX)</td>
<td></td>
</tr>
<tr>
<td>MR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MR</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

![Fig. View of the J-PARC facility](http://ptep.oxfordjournals.org/)

“K0 at Tokai”
Experimental hall

Hadron Experimental Facility (HEF)

- Intense 30 GeV proton beam with around 50% duty factor
- Secondary neutral beam is extracted (16°) and directed to KOTO detector
Highly collimated neutral “pencil” beam

KOTO neutral beam

Fig. Depiction of neutral beam line production

target to detector distance = 21.5 m
Experimental method

Principle

- Signature is a pair of photons from the pion decay and a finite transverse momentum

- **2γ and nothing else** - Detect energy and position of photons from pion decay with an electromagnetic calorimeter, and reconstruct vertex position and momentum

Major Obstacles

- Background contribution from $K_L \rightarrow 2\pi^0$ with non-detected photons, other decay channels, and neutron interactions mimicking signals

![Graph showing $K_L$ momentum distribution](image)

$P_K \sim 1.4$GeV/c

![Diagram of $K_L$ momentum distribution](image)

$M_{\pi^0}^2 = (E_1 + E_2)^2 - (P_1 + P_2)^2$

$\cos \theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$
Experimental method

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

Neutral beam line

“$2 \gamma$ +Nothing+Pt”

Assuming $2 \gamma$ from $\pi^0$, Calculate z vertex.

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

Calculate $\pi^0$ transverse momentum

Fig. Monte Carlo sample of signal distribution

Rec. Pt vs. Rec. $Z$ [mm]

signal region

Rec. $P_T$ vs. Momentum [MeV/c]

signal region

Rec. Z [mm]

Fig. Monte Carlo of signal and background distributions

Arb. Units

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Hermetic detector

Radius = 3m

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

Fig. Outer vacuum container houses all main KOTO detectors

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Background reduction is crucial!

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

Table. Branching ratios of various Kaon decays (PDG)

Two sub-system design:

- Cesium Iodide Calorimeter (CsI)
  - Main detector of the KOTO experiment
- Hermetic veto detectors
  - ~1000 channels

Fig. KOTO detector components
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. 1. Schematic side view of the detector setup of the J-PARC KOTO experiment. Most of the detectors are contained in the cylindrical vacuum vessel of 3.8 m diameter and 8.7 m in length. FB, NCC, MB, and R5364) with Cockcroft-Walton (CW) bases are utilized for the OEV counters since they shared the same composition and cross-sectional shapes in order to hit the barrel detector (MB in Fig. 1) with an energy about 10 MeV. However, this low energy photon may not be detected with a 20% probability due to fluctuations of MB veto, which is made of 12-mm-thick stainless steel with an inner diameter of 1.93 m. OEV is a group of 44 lead scintillator-sandwich counters. They have different thicknesses of 37 mm and 43 mm, respectively. The inner region of the calorimeter consists of 2240 undoped CsI crystals with a 25 mm cross-section, while the outer region has 2832 CsI (25 mm x 25 mm) crystal blocks. All crystals are 500 mm long. Hamamatsu R5330 1.5 inch PMTs are used for the large crystals. Those PMTs were originally used at the KTeV experiment and re-used in the KOTO experiment. The CsI calorimeter, the cylindrical support structure of the vacuum vessel, which is made of 12-mm-thick extruded polymethyl-methacrylate 20%), is suitable to be used under high rate condition, the time resolution of a few nanoseconds is required for the OEV counters. In addition, they need to operate stably in vacuum under the heavy load of the CsI crystals.
KOTO detectors

Neutron Collar Counter (NCC)

- NCC is used to suppress and estimate neutron background
- Measure flux and spectrum of halo neutrons
- Undoped CsI crystals ($X_0=1.9$ cm) read out by wavelength shifting fibers arranged in 3 optically separated regions

Background reduction is crucial!

Fig. KOTO detector components

Fig. Front and side view of the NCC

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KOTO detectors

Photon Veto

- Used to diminish background from other $K_L$ decays ($K_L \rightarrow 3\pi^0, 2\pi^0, \pi^+ \pi^- \pi^0$), and $\pi^0$ from halo neutron
- Upstream and decay region: Main (MB) and Front Barrel (FB), and Outer Edge Veto (OEV)
- Downstream: Collar Counters (CC04-CC06), Beam Hole Photon Veto (BHPV), and Beam Hole Guard Counter (BHGC)

Fig. KOTO detector components
KOTO detectors

Charged Veto

- Used to suppress background from other $K_L$ decays ($K_L \rightarrow \pi^+ \pi^- \pi^0$, $\pi^+ e^- \nu$).

- Upstream and decay region: Barrel Charged Veto (BCV), Charged Veto (CV), Liner Charged Veto (LCV).

- Downstream: Collar counters (CC04-CC06), Beam Hole Charged Veto (BHCV), and Beam Pipe Charged Veto (BPCV).

Fig. KOTO detector components
KOTO detectors

Charged Veto (CV)

- Parameters
  - γ
  - π
  - \(10^{-5}\) Pa

- Challenges
  - ~10

- FADC board

- Lead/Aerogel Cerenkov counter

- Catching photons down the hole

Charged Veto (CV)

- 0.8 mm CFRP reinforced
- MPPC scintillator fiber both end read out
- 8-10 p.e/100KeV
- inefficiency < 10^{-3}

Beam Hole Photon Veto (BHPV)

- lead aerogel Cherenkov detector

Neutron Collar Counter (NCC)

Collar Counter (CC04)

- Plastic scintillator
- CsI

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Friday, April 19, 2013

The waveforms are then digitized at 125 MHz or 500 MHz at half-maximum (FWHM) using a 10-pole Bessel filter. Shaped into a Gaussian waveform of.

To meet these requirements, the analog PMT signals are for the data acquisition system are 14-bit dynamic range for to receive PMT signals from approximately 3000 calorimeter types of ADC modules, 125 MHz and 500 MHz, are used in order to reach the Standard Model sensitivity, higher beam flux of.

In May, 2013, the experiment accumulated data with 14.

The KOTO experiment is located at J-PARC in Tokai, Ibaraki, Japan. The goal of the KOTO Experiment is to.

Our data acquisition system consists of two types of ADC 14 modules and three levels of triggers, as shown in Fig. 2. Two

In the June 2016 run, we implemented the feature of feeding hits of calorimeter to measure the energy and the position of the 550 MeV onto the CsI calorimeter and no activity in the veto detectors. By fitting the Gaussian waveform with points 8 ns apart, we can reconstruct the timing of the PMT signals up to 99.9% towards detecting charged decay processes to identify such event - neutral

The KOTO detectors are calibrated using beam data. A lossless bit-packing

The L3 trigger uses both Vertex 5 and Vertex 4 FPGA. The data output Compression 

The master L1 trigger module outputs the information for each veto detector threshold. Upon a L1 accept, the ADC modules transmit the buffered data to the L2 trigger. Different

The L1 trigger cut of requires a minimum 550 MeV energy deposit in the CsI calorimeter and makes the trigger decision. The L1 trigger decision is made. The L1 trigger decision is made

The electronics hardware is an energy of 30 GeV . The accelerated protons generate K decays. Due to the two missing neutrinos, our signal requires any other charged or neutral decay products and veto these

As a software trigger. Black indicates the data being transferred. Fig. 2: The KOTO data acquisition system flow chart. The L1

Permanent Storage at KEK
DAQ trigger levels

- **Level 1 Request** = number of triggers that meet Level 1 requirement (CsI E > E threshold [MeV] + no Veto)

- **Level 1 Accept** = number of triggers that are passed to L2 when L2 buffer is not full

- **Level 2 Accept** = number of triggers that meet Level 2 COE (>165 mm) requirement

- **Level 3** = number of events built and stored
Chronicle of KOTO runs

First physics run

Operation of Hadron facility was stopped.
A new search for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 X^0$ decays

J-PARC KOTO collaboration

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 $0.34 \pm 0.16$ 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 ($K_L \rightarrow \pi^0 \nu \nu$)

First Search: Upper limit on BR ($K_L \rightarrow \pi^0 X^0$)
Distributions of reconstructed events

before veto cuts

K_{L}\rightarrow 3\pi^0

K_{L}\rightarrow 2\pi^0

after veto cuts

K_{L}\rightarrow 3\pi^0 MC

Other K_{L} MC

Data
First run takeaways

Table 1  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 neutron ~70%

background source

1. Halo neutrons hitting NCC ($\pi^0$)
2. Halo neutrons hitting CsI
3. $K_L \rightarrow \pi^+\pi^-\pi^0$

Fig. Reconstructed $\pi^0$ Pt vs. decay vertex position
2. Neutron-induced background

In the 2013 analysis, we found that beam-halo neutrons hitting the CsI calorimeter are the dominant source of our background. A beam-halo neutron hits the CsI calorimeter and forms a primary hadronic shower. In the interactions, a secondary neutron can be emitted and it produces a secondary shower after traveling inside the calorimeter (Figure 2). These two shower clusters can be observed without hits in any veto detectors. If such an event is reconstructed in the signal box, it will be a background. In 2013, the estimated number of this “neutron-induced background” was 0.18 out of the total background events of 0.34.

3. Methods to suppress neutron-induced background

We have developed several methods to suppress the neutron-induced background. The key of the background reduction is to distinguish a photon cluster from a neutron cluster using calorimeter hit information. The methods named “Shape $\chi^2$,” “Cluster Shape Discrimination,” and “Pulse Shape Likelihood” that we developed will be explained in this paper. The first two use cluster shape information, and the last one uses waveform information from the hits in the calorimeter. The Shape $\chi^2$ method has been used in the 2013 analysis, and the Cluster Shape Discrimination and the Pulse Shape Likelihood are newly developed after that.
Updates to reduce region 1

Neutron induced events

- Analysis on neutron sample generated by using a 10mm Al target
  - Neural Networks (NN) cuts to select between hadronic and photon cluster based on cluster shape dynamics (Cluster Shape Discrimination)
  - Shape $\chi^2$ compares observed energy deposit with the expected. The sum is taken over 27 x 27 crystals around cluster center
  - Pulse shape likelihood cut uses waveform information, hadronic showers tend to have a longer tail

hadronic and photon cluster identification performed using energy and timing information

Ex. inputs: energy $X^2$, $E_{\text{diff}}$, timing $X^2$

Fig. Neural Net outcome of cluster shape cut
Updates to reduce region 1

Neutron induced events

- Analysis on neutron sample generated by using a 10mm Al target
  - Neural Networks (NN) cuts to select between hadronic and photon cluster based on cluster shape dynamics (Cluster Shape Discrimination)
  - Shape $\chi^2$ compares observed energy deposit with the expected. The sum is taken over 27 x 27 crystals around cluster center
  - Pulse shape likelihood cut uses waveform information, hadronic showers tend to have a longer tail

![Fig. Pulse shape likelihood ratio](image1.png)

1/10 neutron reduction with 90% signal acceptance

![Fig. Pulse shape likelihood ratio](image2.png)

1/10 BG reduction & 90% signal acceptance
Updates to reduce region 2

Reduction of produced halo neutrons

- Improved aligned surfaces of collimators
  - Beam profile monitor
- Vacuum window replaced (thinner)
  - 125 μm → 12.5 μm reduce neutron interactions

Fig. Movable collimators aligned with BPM

Fig. Beam Profile Monitor

Fig. Polymide vacuum window
Updates to reduce region 3

Upgrade of Beam Hole Charge Veto (BHCV)

- Suppress $K_L \rightarrow \pi^+ \pi^- \pi^0$
- Previous design: plastic scintillator
- Now: 3 layers of wire chambers reduced count rate by 65%
- Acceptance loss reduced by ~40% due to an achieved 99% efficiency in all layers

In-beam Charged Veto (Wire chamber CF$_4$+C$_5$H$_{12}$ gas)

**Fig. 2.1** Cross-sectional view of the KOTO detector. The $K$-axis points in the beam direction, the positive $L$-axis points in the beam direction, and the negative $\pi$-axis points away from the beam.

**Fig. 2.** Cross-sectional view of the KOTO detector. The $K$-axis points in the beam direction, the positive $L$-axis points in the beam direction, and the negative $\pi$-axis points away from the beam.

**Fig. Counting rates as function of beam power**

<table>
<thead>
<tr>
<th>beam power [kW]</th>
<th>plastic scintillators</th>
<th>wire chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>18</td>
<td>14</td>
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<td>22</td>
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<td>36</td>
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Updates to reduce region 3

Beam Pipe Charged Veto (BPCV)

- BPCV ~ 10% BG reduction

Fig. Depiction of BPCV placement

Events without BPCV veto

Events with BPCV veto

Fig. Reconstructed Pt vs. decay vertex position

Fig. BPCV detector
Other improvements

With expected higher beam power, upgrades are essential

- Additional veto detector(s)
- New barrel detector
- DAQ improvements
- Both-end read out of CsI
Other improvements

Beam Hole Guard Counter (BHGC)

- In-beam photon counter was added to tag photons that escape through the beam hole
- Lead plate in front of acrylic Cherenkov detector
- Estimated 90% rejection of 1 GeV photons

The detection gap due to shorter path

K_L → 2π^0

KOTO detectors to stop neutrons and kaons, and by requiring a coincidence with an in-beam event caused by 1 GeV photons going through the detection gap will be rejected.

In March 2015 (Figure 4).

Confirmed that the BHGC response was well reproduced with MC simulations by selecting 130 mm away from the beam axis. With this design, 90% of the background was decided to be 130 mm away from the beam axis.

Other improvements

BHGC. The BHGC is an acrylic Cherenkov counter developed to cover the detection gap near the beam. Based on the stable operation and the expected performance, 90% of the background rejection this one event inside the blind region.

Figure 5.

Figure 6.

We also estimated by a MC simulation.

<table>
<thead>
<tr>
<th>Run</th>
<th>Light yield (p.e.)</th>
<th>Stability as a function of run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr</td>
<td>18200</td>
<td>stable within a few percent</td>
</tr>
<tr>
<td>May</td>
<td>18400</td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>18800</td>
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<tr>
<td>Jul</td>
<td>19000</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Rec.Pi0Pt</th>
<th>Rec.Pi0Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
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<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
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<tr>
<td>7</td>
<td>0</td>
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<tr>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

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Inner Barrel

Fig. Inner barrel prior to being inserted into main barrel detector
New barrel photon veto (IB)

- Aimed at reducing $K_L \rightarrow 2\pi^0$ background
- Sampling calorimeter (25 layers of 5 mm scintillators and 24 layers of 1 mm lead plates)
- 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

**Inner Barrel**

In 2015, we started to make modules as shown in Fig. 3. To bundle the module, we used 0.75 mm-thick stainless band in 9 points. The accuracy of the module production was determined to be less than 1 mm. The modules are supported by 8 rings as shown in Fig. 4. All the production and construction processes were made in KEK. The detector was delivered to J-PARC, then installed in April 2016.

To insert the IB in the MB, the IB detector was pulled on the teflon and construction processes were made in KEK. The detector was delivered to J-PARC, then installed in April 2016. We installed a new photon-veto detector to the KOTO experiment in April 2016. The IB detector is a sampling calorimeter as shown in Fig. 2. It consists of 25 layers of 5 mm thick scintillators and 24 layers of 1 mm lead plates. The inner and outer diameters are 1.5 m and 1.9 m, respectively. The IB detector is shown as blue color.

In May-June 2016, the first physics run with the IB detector was performed. To check the performance of the IB detector, we installed additional scintillator layers inside the MB. The main background is expected to suppress the main background from $K_L \rightarrow 4\pi^0$. We installed a new photon-veto detector to the KOTO experiment in April 2016. The IB detector is a sampling calorimeter as shown in Fig. 2. It consists of 25 layers of 5 mm thick scintillators and 24 layers of 1 mm lead plates. The inner and outer diameters are 1.5 m and 1.9 m, respectively. The IB detector is shown as blue color.

After installation, the performance of the IB detector was evaluated with the data. Fig. 5 shows the timing resolution evaluated with cosmic-rays passing through the MB and IB detectors. As shown in Fig. 6, the MC estimated suppression of $K_L \rightarrow 2\pi^0$ is also displayed. The new IB detector is expected to suppress the main background from $K_L \rightarrow 4\pi^0$.
## DAQ improvements

<table>
<thead>
<tr>
<th>Component</th>
<th>2013</th>
<th>Summer 2015</th>
<th>Fall 2015</th>
<th>Summer 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADC</strong></td>
<td>16 Crates Uncompressed data</td>
<td>17 Crates Uncompressed data</td>
<td>17 Crates Compressed data</td>
<td>18 Crates Compressed data</td>
</tr>
<tr>
<td><strong>FANOUT</strong></td>
<td>16 FANOUT Module</td>
<td>32 FANOUT Module</td>
<td>32 FANOUT Module</td>
<td>32 FANOUT Module</td>
</tr>
<tr>
<td><strong>MACTRIS</strong></td>
<td>Clock to two trigger boards</td>
<td>Clock to three trigger boards</td>
<td>Clock to three trigger boards</td>
<td>Clock provided to four trigger boards</td>
</tr>
<tr>
<td><strong>L2</strong></td>
<td>Firmware design by schematic only</td>
<td>Firmware design using Verilog with compression</td>
<td>Firmware design using Verilog with compression</td>
<td>Firmware design using Verilog with compression</td>
</tr>
<tr>
<td><strong>L3</strong></td>
<td>Mandolin Ethernet switch for event building</td>
<td><strong>Banjo</strong> cluster (2 node type) Infiniband for event matching and building</td>
<td><strong>Banjo</strong> Infiniband for event matching and building</td>
<td><strong>Banjo</strong> Infiniband for event matching and building</td>
</tr>
</tbody>
</table>
DAQ performance

Improved DAQ efficiency:

○ Data acquisition system has been steadily improved to accommodate larger data sets with increasing beam power

○ From 75-80% up to 90-95%

Fig. DAQ efficiency
Current status

First physics run

Operation of Hadron facility was stopped.
Distributions of reconstructed events

Data/MC Comparisons

- \( K_L \rightarrow 3\pi^0 \)
- \( K_L \rightarrow 2\pi^0 \)
- \( K_L \rightarrow 2\gamma \)

Data is well reproduced

Black: Data
MC: Monte Carlo
Distributions of reconstructed events

Data/MC Comparisons

KL → 3π⁰

KL → 2π⁰

Distributions are well reproduced
Preliminary results

Table 2. Estimated numbers of background events in the signal region for run62 data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>KL→2π⁰</td>
<td>0.04±0.03</td>
</tr>
<tr>
<td>KL→π⁺π⁻π⁰</td>
<td>0.04±0.01</td>
</tr>
<tr>
<td>Halo neutrons hitting NCC (upstream)</td>
<td>0.04±0.04</td>
</tr>
<tr>
<td>Halo neutrons hitting CSI</td>
<td>0.05±0.02</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.17±0.05</strong></td>
</tr>
</tbody>
</table>

Fig. Reconstructed π⁰ P_T vs. decay vertex position

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**K_L flux estimation**

Measured K_L yield for each normalization decay mode (K_L->3π^0, 2π^0, 2γ):

- Estimated from number of reconstructed events in data after application of selection requirements for mode, acceptance of mode, BR(mode), and Protons on Target (POT)

![Graph showing KL flux/2^{14}POT for different normalization modes (3π^0, 2π^0, 2γ). The graph indicates an average of (3.569 ± 0.013) x 10^7.]
K_{L} flux estimation

Measured K_{L} yield for each normalization decay mode (K_{L}->3\pi^{0}, 2\pi^{0}, 2\gamma):

- Estimated from number of reconstructed events in data after application of selection requirements for mode, acceptance of mode, BR(mode), and Protons on Target (POT)

- Systematic uncertainty estimated from single cut efficiency

![Graph showing KL flux/2^{14}POT with normalization modes (3\pi^{0}, 2\pi^{0}, 2\gamma).]

\text{Average} = (3.569 \pm 0.013 \pm 0.200) \times 10^{7}
Single event sensitivity

Single Event Sensitivity (SES) is a measure of signal ($K_L \rightarrow \pi^0 \nu \nu$) sensitivity and is obtained from remaining events in normalization modes after applying kinematic and veto cuts and total acceptance.

$$SES = \frac{1}{K_{yield} \cdot Acceptance_{signal}}$$

Increased Single Event Sensitivity attributed to:

- Measured $K_L$ flux
- Wider signal box due to improved BG reduction methods and upgraded detectors
- Signal acceptance of cuts is roughly the same

<table>
<thead>
<tr>
<th>Experimental Run</th>
<th>SES</th>
</tr>
</thead>
<tbody>
<tr>
<td>E391a</td>
<td>$11.1 \times 10^{-9}$</td>
</tr>
<tr>
<td>Run49</td>
<td>$12.9 \times 10^{-9}$</td>
</tr>
<tr>
<td>Run62</td>
<td>$\sim 5.9 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Increased sensitivity by a factor of 2
Projections

First physics run

Operation of Hadron facility was stopped.
Estimate of all 2015 data

<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>&lt;0.34</td>
</tr>
<tr>
<td>Total</td>
<td>0.17±0.05</td>
<td>0.77</td>
</tr>
</tbody>
</table>

single event sensitivity = 1.1 x 10^{-9}
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($K_L \rightarrow \pi^0 X^0$) upper limit of $< 3.7 \times 10^{-8}$ (90% confidence), which is the first upper limit for $X$ mass of 135 MeV/c

Present

- We have collected a data set (2015 runs) roughly 20 times larger than the 2013 run
- Confirmed that major BG observed 2013 run are well suppressed
- Analysis is on going:
  - 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 and a SES of $1.1 \times 10^{-9}$ for the entire 2015 data set
- After completing analysis of all 2015 data, we expect to approach Grossman-Nir limit (theoretical model independent limit $\approx 1.5 \times 10^{-9}$)
Next steps

- Overcome the background level and improve sensitivity $\sim 10^{-11}$
- Additional detector upgrades (2018)
- DAQ upgrades (2017~)
- Beam power increase 42kW $\rightarrow$ 100kW (2019)
- Explore new physics with a direct measurement
- Extension of hadron hall (KOTO Step 2)
Outlook

Branching ratio

Littenberg
E731(\(e^+e^-\gamma\))
E799(\(e^+e^-\gamma\))
KTeV(\(\gamma\gamma\))
KTeV(\(ee\gamma\))
E391a: first(\(\gamma\gamma\))
E391a: Run2(\(\gamma\gamma\))
E391a: final(\(\gamma\gamma\))
KOTO(\(\gamma\gamma\))

Grossman-Nir limit

SM Prediction

GN = 1.5 \times 10^{-9}

E731: FNAL
KTeV: FNAL/KEK
E391a: KEK
KOTO: JPARC
Thank You
Additional Information
Output of Calorimeter system

- PMT holder (carbon steel SS400)
- CsI crystal
- Silicon cookie
- UV filter
- Magnetic shield (permalloy)
- Single-ended output
- Differential output
- Category 6 Ethernet cable
- ADC/trigger system
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>
Background estimations

Estimation method

- $K_L \rightarrow 2\pi^0$ and $\pi^+\pi^-\pi^0$ estimated with MC and accidental overlay file

- NCC was estimated with MC and normalization was performed by events in NCC region

- Neutron events were estimated with the use of an aluminum target placed on the beam line
Run 62 background

Neutron Background

Recycled

KL→π+π−π0 Background

KL→2π0 Background

Reconstructed Pt vs vertex-z [wBPCV]

Events by the minimum bias trigger data, described in Sec. 7.3.1. The left one shows the number of observed MC events in signal box, with corrections for various detector inefficiency, cutout holes with a size of 0.033 mm, and the efficiency small and reduce this type of background hence needs to be considered for optimization of detection threshold.

KL→2π0 Background

ALL MC observed (events in signal box)
Next steps

Neutron shower reduction:

- Adding a two-sided read out to the CsI crystals

- crystals:
  - interaction length ~38 cm
  - radiation length \((X_0)\) ~1.9 cm
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

Light from neutron
Light from gamma

500 MeV γ
1 GeV neutron (downstream incident)

~1 order rejection!
Study on going
Physics Trigger:

- CsI, MB, CV, NCC, and CC03 veto detectors
Flux calculation

Acceptance calculated as:

\[ A_{\text{mode}} = \left( \frac{\# \text{ Reconstructed}_{\text{mode}}}{\# \text{ Simulated}_{\text{mode}}} \right) \]

K_L yield found as:

\[ #K_L = \frac{\# \text{ of. Rec. } K_L_{\text{(data)}}}{(\text{Acceptance}_{\text{mode}} \times \text{BR}_{\text{mode}})} \]

Flux calculated as:

\[ #K_L / \text{POT} = K_L \text{ yield} / (\text{POT}_{\text{runs}} \times \text{POT }_{\text{norm factor}}) \]

\[ \text{POT}_{\text{runs}} = 2.61 \times 10^{16}, \ \text{POT }_{\text{norm factor}} = 2.00 \times 10^{14} \]
## $K_L$ flux estimation

<table>
<thead>
<tr>
<th>Mode</th>
<th>N (Data Rec.)</th>
<th>Acceptance (MC)</th>
<th>Acceptance (MC) x BR (mode)</th>
<th>Yield = Ndata/ (AxBR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow 3\pi^0$</td>
<td>44365 ± 210</td>
<td>$(4.866 \pm 0.022) \times 10^{-5}$</td>
<td>$(9.499 \pm 0.072) \times 10^{-6}$</td>
<td>$(4.645 \pm 0.042) \times 10^{9}$</td>
</tr>
<tr>
<td>$K_L \rightarrow 2\pi^0$</td>
<td>1032 ± 32</td>
<td>$(2.526 \pm 0.003) \times 10^{-4}$</td>
<td>$(2.183 \pm 0.080) \times 10^{-7}$</td>
<td>$(4.709 \pm 0.159) \times 10^{9}$</td>
</tr>
<tr>
<td>$K_L \rightarrow 2\gamma$</td>
<td>3113 ± 56</td>
<td>$(1.259 \pm 0.005) \times 10^{-3}$</td>
<td>$(6.887 \pm 0.080) \times 10^{7}$</td>
<td>$(4.521 \pm 0.097) \times 10^{9}$</td>
</tr>
</tbody>
</table>

### FLUX

<table>
<thead>
<tr>
<th>Mode</th>
<th>Chen (Run62-24kW)/2E14 POT</th>
<th>Lin (Run62-24kW)/2E14 POT</th>
<th>Beckford (Run62-24kW)/2E14 POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow 3\pi^0$</td>
<td>$(3.582 \pm 0.021) \times 10^7$</td>
<td>$(3.57 \pm 0.020) \times 10^7$</td>
<td>$(3.583 \pm 0.032) \times 10^7$</td>
</tr>
<tr>
<td>$K_L \rightarrow 2\pi^0$</td>
<td>$(3.613 \pm 0.113) \times 10^7$</td>
<td>$(3.61 \pm 0.113) \times 10^7$</td>
<td>$(3.628 \pm 0.122) \times 10^7$</td>
</tr>
<tr>
<td>$K_L \rightarrow 2\gamma$</td>
<td>$(3.464 \pm 0.064) \times 10^7$</td>
<td>$(3.46 \pm 0.064) \times 10^7$</td>
<td>$(3.468 \pm 0.074) \times 10^7$</td>
</tr>
<tr>
<td>Average(old)</td>
<td>$(3.549 \pm 0.062) \times 10^7$</td>
<td>$(3.55 \pm 0.045) \times 10^7$</td>
<td>$(3.568 \pm 0.045) \times 10^7$</td>
</tr>
</tbody>
</table>
Single event sensitivity

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

Where:

\[ K_{yield} = \frac{K_{flux}}{2 \times 10^{14} \text{POT}} \times \text{POT}_{run} \]

\[ \text{Acceptance}_{signal} = \text{Accidental}_{loss} \times \epsilon_{\text{veto}} \times \epsilon_{\text{kinematics}} \]

<table>
<thead>
<tr>
<th>Experimental run</th>
<th>Kl Flux (Run62)</th>
<th>POT</th>
<th>Accidental Loss</th>
<th>Eff. veto</th>
<th>Eff. kinematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 62</td>
<td>(3.56 ± 0.013) \times 10^7</td>
<td>2.05 \times 10^7</td>
<td>0.511</td>
<td>0.645</td>
<td>1.44 \times 10^{-3}</td>
</tr>
</tbody>
</table>
Systematic Uncertainties
Partial acceptance

Partial Acceptance for $i_{th}$ cut or veto is:

- Partial Acceptance: $PA^i = \frac{\text{# of events with all cuts including cut } \{i\}}{\text{# of events excluding cut } \{i\}}$

Fractional Difference is calculated as:

$$FD^i = \frac{PA^i_{data} - PA^i_{data}}{PA^i_{data}}$$

Systematic Error is calculated as:

$$\sigma = \sqrt{\frac{\sum (FD^i / PA^i_{data})^2}{\sum (1/PA^i_{data})^2}}$$
Partial acceptance

Systematic Errors $KL\rightarrow 3\pi^0$ (24kW):

- Kinematic cuts: Beckford (0.3%)
- Vetos: Beckford (2.6%)
Partial acceptance

Systematic Errors $K_L \rightarrow 2\pi^0$ (24kW):

- Kinematic cuts: Beckford (3.3%)
- Vetos: Beckford (4.2%)
Partial acceptance

Systematic Errors KL→2γ (24kW):

- Kinematic cuts: Beckford (1.39%)
- Vetos: Beckford (25.9%)