

# Status of the J-PARC KOTO experiment

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**Abstract.** The KOTO experiment is dedicated to observe the rare decay  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  at J-PARC. The rare decay  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  breaks the CP symmetry directly and is highly suppressed in the Standard Model. This mode is a powerful tool to measure Standard Model parameters and to search for new physics beyond the Standard Model because its theoretical uncertainty is small.

We performed the first physics run in May 2013 and collected 20 times more data than the first physics run since 2015. In this paper, results of the first physics run, detector upgrade work after the first physics run, and analysis status of 2015 data are reported.

## 1. Introduction

The rare decay  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  provides us one of the best probes for understanding CP violation. The decay breaks the CP symmetry directly. This decay is highly suppressed in the Standard Model because it occurs through a flavor-changing neutral current process. Owing to this, this decay can access indirectly very high energy scale which cannot be reached directly by accelerators [1, 2]. In addition, the contributions from new physics can be estimated precisely because the theoretical uncertainty on this mode is only a few percent. The branching ratio of this decay mode is predicted to be  $(3.00 \pm 0.30) \times 10^{-11}$  in the Standard Model [3]. On the other hand, the current limit on this decay is  $2.6 \times 10^{-8}$  at the 90% confidence level, which was set by the KEK E391a experiment [4].

The KOTO experiment at J-PARC Main Ring accelerator is the successor of the E391a experiment and aims to observe the  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  decay. We had built a new beam line and constructed the new detector system and DAQ system to achieve a sensitivity of  $10^{-11}$ .

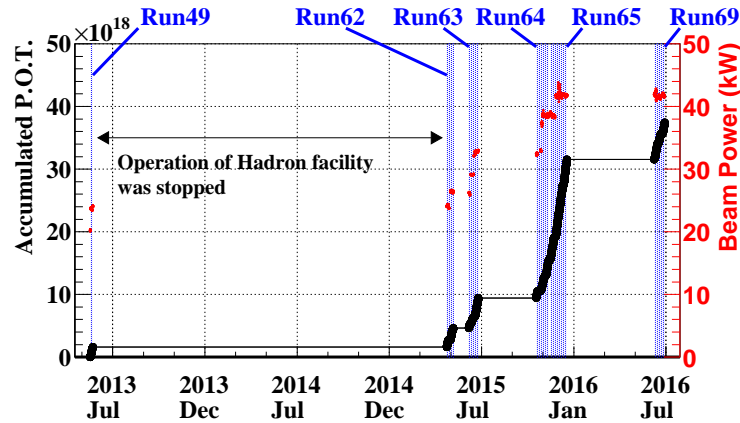
We took the first physics run data in 2013, but we were able to take only 4 days of data in this time due to an incident at Hadron Experimental Facility. After that, the operation of the facility was stopped for two years to renovate safety of the facility. From April 2015, the facility restarted beam operation. We restarted physics data taking and collected 20 times more data than the first physics run, as shown in figure 1.

In this paper, results of the first physics run, detector upgrade work after the first physics run, and analysis status of 2015 data are reported.

## 2. Experiment

A proton beam of 30-GeV was extracted from the Main Ring accelerator to the hall of J-PARC Hadron Experimental Facility every 6 seconds with a 2-second duration, and was injected into the 66-mm-long gold target. The  $K_L^0$ 's produced in the target were transported to the KOTO





**Figure 1.** This plot shows the accumulated protons on the target (P.O.T.) as a function of time. Run49 is the first physics run. In this plot, beam power of the primary proton is also shown by the red points. The beam power increased gradually and the current beam power became two times higher than the beam power at the first physics run.

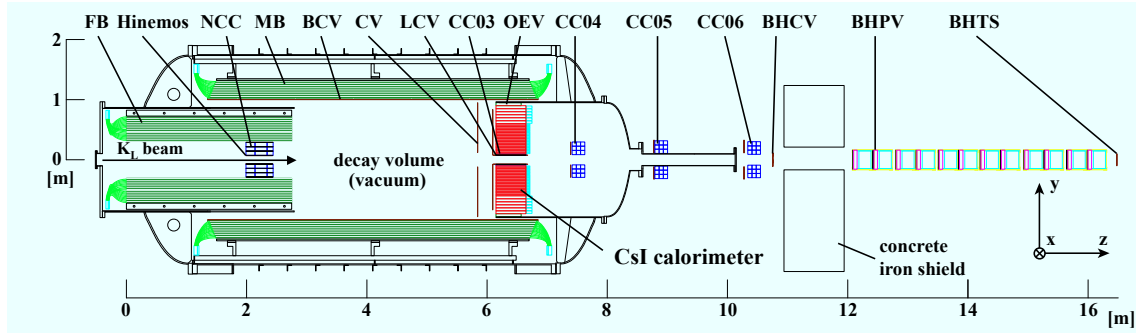
detector system through the “KL beam line” located along  $16^\circ$  line with respect to the primary proton beam line. The KL beam line consisted of two collimators, a sweeping magnet, and a lead photon absorber.

The schematic view of the KOTO detector system is shown in Fig. 2. Most of KOTO detectors were located inside a vacuum tank to avoid  $\pi^0$  production through the interaction between beam neutrons and residual gas. The vacuum tank consisted of the front section, the middle section, and the end cap section. Large lead-scintillator sandwich counters called “Front Barrel (FB)” and “Main Barrel (MB)” were installed inside the front section and the middle section, respectively. A photon detector called “Neutron Collar Counter (NCC)” was located inside FB to separate the decay region from the upstream region. An electromagnetic calorimeter made of 2716 undoped CsI crystals was installed in the end cap section. The front of the calorimeter was covered with a set of plastic scintillators, named “Charged Veto (CV)”. Behind the calorimeter, a photon veto detector called “Collar Counter04 (CC04)” was placed to detect particles that escape through the beam hole in the calorimeter. At the downstream of the vacuum tank, additional two “Collar Counters” and “Beam Hole” veto detectors were located to detect particles from  $K_L^0 \rightarrow \pi^0 \pi^0$  decays passing through the beam hole.

### 3. Results of the first physics run

At first, the analysis method is described briefly. The energies and positions of the two photons from the  $\pi^0$  decay were measured with the CsI calorimeter. The decay position of the  $\pi^0$  was reconstructed on the beam axis, assuming the invariant mass of the two photons to be the  $\pi^0$  mass. The transverse momentum ( $P_T$ ) of the  $\pi^0$  was also calculated. We required a finite transverse momentum for signal candidates because neutrinos should have carried away a finite transverse momentum. A series of event selection criteria was imposed on the reconstructed  $\pi^0$  kinematics and the hit information of the veto counters. Details on the selection criteria are described in Ref [5].

The signal search plane of the first physics run is shown in Fig. 3. Several events are clustered at  $z = 2000\text{--}2600$  mm. In these events, neutrons in the beam halo (halo neutrons) interacted with NCC and produced  $\pi^0$ . The two photons from the  $\pi^0$  hit the CsI calorimeter. The decay vertexes of those were reconstructed at the NCC location that was outside the signal region. The

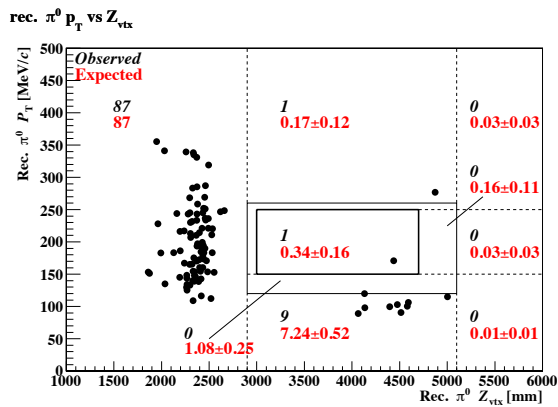


**Figure 2.** Cross-sectional side view of the KOTO detector system. The  $K_L^0$  beam comes in from the left hand side. Also shown is the coordinate system used in this paper:  $x$  is the horizontal,  $y$  is the vertical, and  $z$  is the beam direction. The origin of the coordinate is set at the upstream end of FB.

events in the low  $P_T$  region came from  $K_L^0 \rightarrow \pi^+\pi^-\pi^0$  decays. In those events, charged pions from the  $K_L^0 \rightarrow \pi^+\pi^-\pi^0$  decay passed through the beam hole of the calorimeter and interacted with the beam pipe before they were detected by veto detectors located downstream. The event in Fig. 3 in the region above the signal box is likely to be caused by halo neutrons hitting the CsI calorimeter. We suspected that the single neutron could make two clusters through several hadronic interactions in the calorimeter.

We found one event in the signal box while 0.34 background (BG) events were predicted. We set an upper limit on the  $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$  decay to be  $5.1 \times 10^{-8}$  at the 90% confidence level [6]. We also set an upper limit on the  $K_L^0 \rightarrow \pi^0 X^0$  decay to be  $3.7 \times 10^{-8}$  at the 90% confidence level, where  $X^0$  is an invisible particle with the mass close to  $\pi^0$ ; it was recently pointed out that the experimental search for a weakly-interacting light particle had a loophole around the  $\pi^0$  mass region [7, 8].

The numbers of background events expected in the signal region are summarized in Table 1. The most serious background events in the first physics run were due to halo neutrons hitting the calorimeter.



**Figure 3.** Scatter plot of reconstructed  $P_T$  vs  $z$  after imposing all selection criteria. The inner box is the signal region. The numbers in black show the numbers of observed events, and the numbers in red show the numbers of expected background events.

#### 4. Detector Upgrade

After the first physics run, we upgraded several detectors to suppress BG events in the first physics run.

Background source	The number of background events
Halo neutrons hitting the CsI Calorimeter	$0.18 \pm 0.15$
Kaon decay events	$0.10 \pm 0.04$
Halo neutrons hitting the NCC	$0.06 \pm 0.06$
Sum	$0.34 \pm 0.16$

**Table 1.** Estimated numbers of background events in the signal region for the first physics run.

Downstream detectors were upgraded before the 2015 run. To suppress  $K_L^0 \rightarrow \pi^+\pi^-\pi^0$  events, we replaced the vacuum pipe extended from the vacuum tank to the front of CC06 with thinner one, and we installed new scintillator counters outside of the vacuum pipe to detect charged particles generated by the interaction between charged pions and the vacuum pipe. To increase the detection efficiency for the photon escaping along the beam axis, we added four modules of “Beam Hole Photon Veto (BHPV)” (see Fig. 2.), which is made of lead and Cherenkov counter with aerogel [9] and to discriminate photons from neutrons. We also installed, in the downstream of BHPV, new photon counters made of lead and acrylic radiator to detect photons escaping detection by BHPV.

An additional barrel photon detector called “Inner Barrel(IB)” was installed to the inside of MB before the 2016 run to reduce  $K_L^0 \rightarrow 2\pi^0$  BG events. The IB is a sandwich calorimeter which consists of 25 pairs of 5-mm-thick plastic-scintillator plates and 1-mm-thick lead plates.

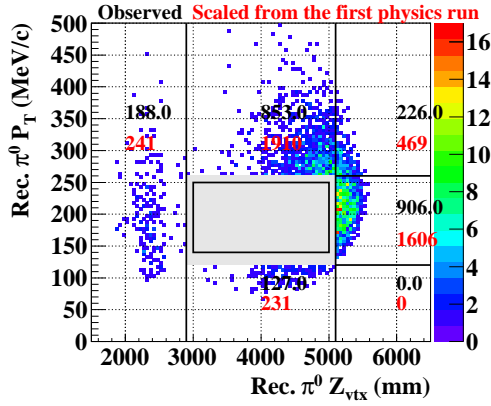
## 5. Analysis status of 2015 data

We developed new cuts to suppress background events observed in the first physics run and checked the effect of new cuts for background reduction by using Run62 data (see Fig. 1). After that, we estimated the signal sensitivity and the number of background events in the signal box.

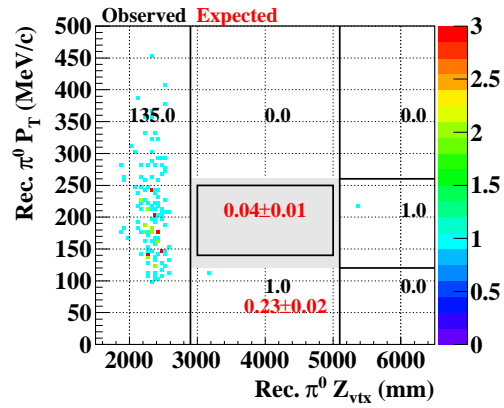
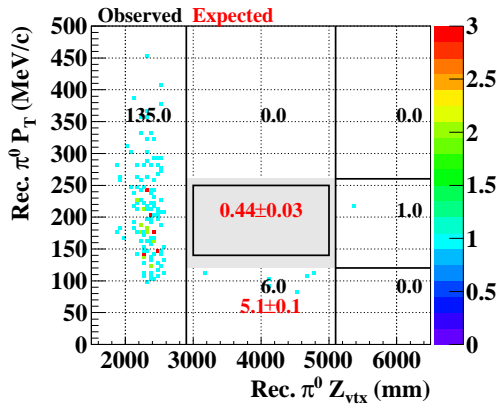
### 5.1. Study of background reduction

To suppress BG events due to halo neutrons, we tried to reduce the number of halo neutrons. There were two sources of halo neutrons. One was the surfaces of collimators located in the beam line. We re-aligned collimator positions according to the measurements of the beam profile. Another source was the vacuum window located in front of the KOTO detector system which separated the vacuum in the beam line from the vacuum in the decay region. The vacuum window was replaced with a thinner one. These modification reduced the number of background events due to halo neutrons hitting the calorimeter by 50%, as shown in Fig. 4. To get further reductions of background events due to halo neutrons, We studied hadron cluster events by using special data. In this data, a 10-mm-thick aluminum disk was inserted into the beam to scatter neutrons into the calorimeter. By using the special data, we developed new cuts to distinguish the clusters made by photons from the clusters made by neutrons. The new cuts improved the rejection of hadron cluster events by one order of magnitude while keeping signal efficiency almost the same as the previous analysis.

To suppress  $K_L^0 \rightarrow \pi^+\pi^-\pi^0$  events, we installed new scintillator counters as mentioned in Section 4. We checked the veto effect of this new counters, as shown in Fig. 5. The reduction of events having small transverse momentum was consistent between data and MC within statistical uncertainties. The number of events expected in the signal region was  $0.04 \pm 0.01$  after the veto cut.



**Figure 4.** Scatter plot of reconstructed  $P_T$  vs  $z$  for samples enhanced neutron events. The gray box is the masked region in the analysis. The numbers in black show the number of events observed in Run62 and the numbers in red show the number of events scaled from the first physics run.

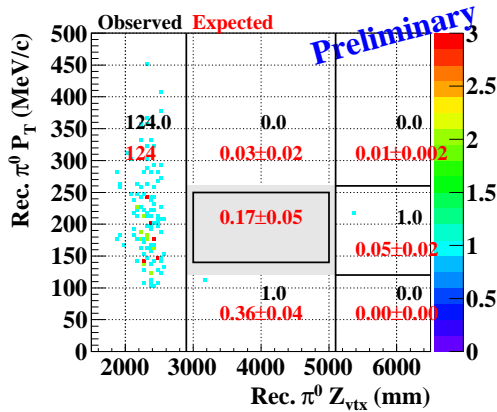


**Figure 5.** The left (right) plot shows scatter plot of reconstructed  $P_T$  vs  $z$  before (after) applying the veto cut of new scintillator counters. By applying the veto cut, the events in the low  $P_T$  region are removed effectively and the number of events expected in the signal box reduces by one order of magnitude.

### 5.2. Sensitivity and BG estimation

The total number of  $K_L^0$ s in Run62 was estimated to be  $(3.72 \pm 0.07) \times 10^{11}$  by using  $K_L^0 \rightarrow 2\pi^0$  samples and it was 1.6 times larger than the first physics run. In Run62, background events due to  $K_L^0 \rightarrow \pi^+\pi^-\pi^0$  and halo neutrons hitting the calorimeter were well suppressed by new cuts as mentioned in the previous subsection. We plan to use a larger signal region than that in the first physics run, which improved signal efficiency by 40%. The single event sensitivity (S.E.S) of the  $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$  decay for Run62 was estimated to be  $5.9 \times 10^{-9}$  preliminarily, which is two times better than the first physics run.

Figure 6 shows the reconstructed  $P_T$  vs  $z$  after imposing all selection criteria. The number of observed events in the downstream region ( $z > 5000\text{mm}$ ) was slightly larger than the number of expected background, but was still within a statistical uncertainty under this small data set. Table 2 summarizes the number of background events expected in the signal region.



**Figure 6.** Scatter plot of reconstructed  $P_T$  vs  $z$  after imposing all selection criteria. The gray box is the masked region in the analysis. The inner box is the signal region. The numbers in black show the number of observed events, and the numbers in red show the number of expected background events.

Background source	The number of background events
$K_L^0 \rightarrow 2\pi^0$	$0.04 \pm 0.03$
$K_L^0 \rightarrow \pi^+\pi^-\pi^0$	$0.04 \pm 0.01$
Halo neutrons hitting the NCC	$0.04 \pm 0.04$
Halo neutrons hitting the CsI calorimeter	$0.05 \pm 0.02$
Sum	$0.17 \pm 0.05$

**Table 2.** Estimated numbers of background events in the signal region for Run62 data.

## 6. Conclusions and Prospects

The KOTO experiment searches for the rare decay  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  at J-PARC. The first physics data was taken in 2013. One event was observed while 0.34 BG events were expected. We set a branching ratio on the  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  decay to be  $5.1 \times 10^{-8}$  at the 90% confidence level. We also set an upper limit on the  $K_L^0 \rightarrow \pi^0 X^0$  decay to be  $3.7 \times 10^{-8}$  at the 90% confidence level, where  $X^0$  is an invisible particle with the  $\pi^0$  mass.

After the first physics run, we updated several detectors to reduce background events found in the first physics run and collected 20 times more data than the first physics run. We checked the reduction of background events by using small data set and confirmed that background events were well suppressed by new cuts.

Next, we will analyze more data to check background events with higher sensitivity and optimize cut conditions to achieve a higher sensitivity.

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