Search for the rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC

KOTO experiment

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Abstract. The KOTO experiment aims to study the CP-violating rare decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC. The analysis of the data set taken in 2016, 2017 and 2018 is reported. In order to reduce backgrounds and to improve the signal acceptance, a new barrel photon detector and a new trigger system were installed and new analysis techniques were developed. The $K_L$ yield was $7.1 \times 10^{12}$. The single event sensitivity was estimated to be $6.9 \times 10^{-10}$, which was improved by a factor of 2 compared to the data set taken in 2015. The number of background events was estimated to be $0.05 \pm 0.02$. Four candidate events were observed in the signal region, and their studies are on-going extensively to find their sources.

1. Introduction

The rare kaon decay $K_L \rightarrow \pi^0 \nu \bar{\nu}$ directly breaks CP symmetry. The branching ratio of this decay mode is expected to be $3.0 \times 10^{-11}$ in the Standard Model (SM) and its theoretical uncertainty is at the order of 2% [1]. Thus this decay is sensitive to new physics beyond the SM. The current best upper limit on the branching ratio was set to be $3.0 \times 10^{-9}$ at the 90% confidence level (C.L.) by the KOTO experiment at the Japan Proton Accelerator Research Complex (J-PARC) with the data set taken in 2015 [2]. An indirect limit, called the Grossman-Nir bound [3], is $1.5 \times 10^{-9}$ derived from the isospin symmetry between the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay modes and the upper limit on the branching ratio of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ set by the BNL E787 and E949 experiments.

2. The KOTO experiment

The KOTO experiment aims to study the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay. A proton beam, accelerated to 30 GeV at the J-PARC main ring and extracted to the Hadron Experimental Facility, hits a gold target. Secondary neutral particles are guided to the 21-m long beam line, consisting of two collimators to make a narrow beam with sharp edges, and a sweeping magnet to remove charged particles. The neutral beam, which consists of neutrons, photons, and $K_L$'s, enters the KOTO detector shown in figure 1. The final state of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is two photons from a $\pi^0$ decay and two undetectable neutrinos. We measure two photons with the CsI calorimeter (CSI), which consists of 2716 undoped CsI crystals, and ensure that there are no other particles with hermetic veto detectors surrounding the decay volume. The waveform of all of the detectors are recorded with 125-MHz and 500-MHz sampling ADCs.
3. Data taking performance
Figure 2 summarizes the data taking performance of the KOTO experiment. We performed the first physics run in 2013 [4]. In 2015, we ran for four months and improved the upper limit on the branching ratio of $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ by an order of magnitude over the KEK E391a experiment [5]. After the 2015 physics run, a new cylindrical photon detector (IB) was installed inside the existed one (MB) to improve the veto efficiency for photons. We upgraded the trigger to count the number of hit clusters in the CSI in 2017. In 2016, 2017, and 2018, 1.5 times more physics data were collected than in 2015. After the 2018 run, we attached MPPCs in front of the CsI crystals of the CSI to distinguish between the neutron and gamma clusters in the CSI, to suppress the neutron induced background.

4. Analysis
For the analysis of the data set taken in 2016 - 2018, we developed new analysis techniques to improve the sensitivity and to suppress backgrounds.

4.1. Event reconstruction and selection
To reconstruct the $\pi^0$, the information on the two photons measured with the CSI was used. First, the crystals with deposit energies in the CSI were grouped into one, as a cluster, based on the energy, the hit timing, and the position information of each crystal because a shower spread...
out to multiple crystals. The energy of the photon was reconstructed from the cluster, and the opening angle ($\theta$) between two photons was calculated as

$$\cos \theta = 1 - \frac{M_{\pi^0}^2}{2E_{\gamma 1}E_{\gamma 2}},$$

where the $M_{\pi^0}$ is the nominal mass of $\pi^0$, and the $E_{\gamma 1}$ and $E_{\gamma 2}$ are the energies of the two photons. Since we used a narrow beam, we assumed the $\pi^0$ decay position to be on the beam axis. From the opening angle and the decay position assumption, the $\pi^0$ decay $Z$ vertex position ($Z_{\text{vertex}}$) and the $\pi^0$ 4-momentum were obtained.

The $\pi^0$ from $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay should have a finite transverse momentum ($P_T$) due to the missing momenta of the two neutrinos. We defined the signal region with the reconstructed $\pi^0$'s $P_T$ and the $Z_{\text{vertex}}$. The selection criteria (cuts) based on the CSI and the veto detector information were used. Events were vetoed if the energy deposition exceeded the threshold and its hit timing existed within a given time window (veto window). The threshold and the veto window were optimized in each detector to achieve the better sensitivity and to suppress backgrounds. The signal region was masked until we finalized the cuts.

4.2. $K_L$ yield and Single Event Sensitivity

For the 2016 - 2018 runs, the number of $K_L$’s entering the KOTO detector ($K_L$ yield) was measured with a $K_L \rightarrow 2\pi^0$ decay sample (figure 3) to be $7.1 \times 10^{12}$ (preliminary). The single event sensitivity (S.E.S) was calculated to be $6.9 \times 10^{-10}$ (preliminary) after imposing all the cuts (figure 4), which corresponds to 0.04 SM expected events; the achieved S.E.S is a factor of two smaller than the 2015 data set.

Figure 3. Reconstructed $K_L \rightarrow 2\pi^0$ mass distribution.

Figure 4. $K_L \rightarrow \pi^0\nu\bar{\nu}$ Monte Carlo simulation in the $P_T$-$Z_{\text{vertex}}$ plot after imposing all the cuts. The red pentagon frame is the signal region.

4.3. Background estimation

There are mainly two types of backgrounds. One is caused by neutrons, and the other is caused by $K_L$ decays.

Hadron cluster background

When a beam-halo neutron hits the CSI and produces a hadronic cluster, another neutron from the hadronic interaction can make another hadronic cluster in the CSI. If those two clusters are misidentified as gamma clusters, the event can be a background (”hadron cluster background”).
To estimate the number of events for this background, a special data set was collected by inserting a 10 mm-thick aluminum plate in the beam to scatter neutrons to the CSI and to let the scattered neutron produces the hadron cluster background. By triggering on two clusters in the CSI with the new trigger system, we collected 9 times more control samples for the hadron cluster background than in 2015.

We updated the cuts to suppress the hadron cluster background from the cuts used in the 2015 analysis, with a large amount of control samples. For the cut using the cluster shape information, we introduced a deep learning method. An additional reduction factor of 2 was achieved compared to the cluster shape cut with the neural network method used in the 2015 analysis. For the cut using the pulse shape difference between gamma and neutron induced pulses in the CsI crystals, we introduced Fourier Fast Transformation (FFT) on the waveform. An additional reduction factor of 1.8 was achieved compared to the pulse shape discrimination cut used for the 2015 data. The selection efficiency of these two cuts on the signal events were kept at the same level as the cuts used for the 2015 data. We also updated the analysis method to estimate the number of hadron cluster background events. There was a contamination in the control sample; when a $K_L$ scatters at the aluminum plate and decays into two photons, the reconstructed $\pi^0$ may have a large $P_t$, and such events can be contained to the control sample. The estimation method was revised to avoid such contamination, and an additional reduction factor of 27 was achieved. The number of events for the hadron cluster background was estimated to be $0.017 \pm 0.002$.

Overlapped pulse background
The overlapped pulse background is caused by an accidental hit overlapping on the pulse that should have been vetoed. As shown in figure 5, if the measured time is shifted to the outside of the veto window due to the overlapped pulse, the event can be a background. The veto window had to be made wide enough to suppress this background. However, due to accidental hits, we lost the signal acceptance by 70%. If we narrow the veto window to increase the signal acceptance, the background will increase. We thus developed a new analysis method with FFT on the waveform of the veto detectors to discriminate the overlapped pulse. By narrowing the veto window with this discriminator, the number of overlapped pulse background events for the $K_L \rightarrow 3\pi^0$ decays and the $K_L \rightarrow \pi^\pm e^\mp \nu_e$ decays were estimated to be < 0.04 and < 0.09 at the 90% C.L., respectively, and the signal acceptance was increased by 10% from the veto scheme used in the 2015 analysis.

![example of overlapped waveform](image)

**Figure 5.** Schematic view of the waveform which caused the overlapped pulse background. This in-time event failed being vetoed because the measured timing is shifted due to the accidental pulse.
Other background sources

Table 1 summarizes the number of estimated background events. The upstream $\pi^0$ background is caused by a $\pi^0$ production by a halo neutron hitting in the NCC detector, which is located upstream of the decay volume. The CV-$\pi^0$ ($\eta$) background is caused by a $\pi^0$ ($\eta$) production by a halo neutron hitting in the CV detector. These backgrounds were studied with the Monte Carlo simulation, and the number of background events was normalized to the data in the side-bands of the control regions. We added the central values of the number of background events, and the number of total background events was estimated to be $0.05 \pm 0.02$. Figure 6 shows the $P_{tZ_{\text{vertex}}}$ plot with the estimated number of background events after imposing all the cuts. The number of observed events is consistent with the number of estimated background events in all the side-band regions.

| Sources                        | No. events |
|--------------------------------|------------|
| Hadron cluster                | 0.017 ± 0.002 |
| Upstream $\pi^0$              | 0.001 ± 0.001 |
| CV-$\eta$                     | 0.03 ± 0.01 |
| CV-$\pi^0$                    | < 0.10     |
| $K_L \to 3\pi^0$ (overlapped pulse) | < 0.04     |
| $K e3$ (overlapped pulse)     | < 0.09     |
| $K_L \to 2\pi^0$              | < 0.18     |
| $K_L \to \pi^+\pi^-\pi^0$    | < 0.02     |
| $K_L \to 2\gamma$             | 0.001 ± 0.001 |
| Total                          | 0.05 ± 0.02 |

5. Observed events

After defining all the cuts, we unblinded the masked region and observed four candidate events inside the signal region and one event inside the blinded region but outside the signal region, as shown in figure 7. We are currently investigating the nature of these events. One of the candidate events has an overlapped pulse in one of the veto detectors as shown in figure 8, despite our low background estimation. We are thus studying more on the source of such backgrounds, and studying further on the other possible sources.

6. Summary

The data set taken in 2016, 2017, and 2018 by the KOTO experiment is being analyzed to study the decay $K_L \to \pi^0\nu\bar{\nu}$, with the S.E.S of $6.9 \times 10^{-10}$. The number of expected background events is $0.05 \pm 0.02$. We observed four candidate events in the signal region, and we are extensively studying the source of these events.

7. Acknowledgements

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Figure 7. $P_t$-$Z_{\text{vertex}}$ plot with all the cuts imposed. The black dashed pentagon frame shows the signal region.

Figure 8. Waveform in one of the candidate events.

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