PROCEEDINGS OF SCIENCE

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

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The KOTO experiment is dedicated to study the rare decay $K_L^0 \to \pi^0 \nu \bar{\nu}$ at the J-PARC 30 GeV Main Ring. The $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay breaks the CP symmetry directly and is highly suppressed in the Standard Model (SM). Thus, this decay is sensitive to new physics beyond the SM, in particular new sources of CP violation. After the first physics run in 2013, the KOTO collaboration improved the detector in order to suppress the backgrounds newly found in the analysis. We resumed physics run in 2015 and collected about 20 times larger amount of data in the year. From the 2015 data analysis, no events were observed with the expected background of 0.4 ± 0.18. We set an upper limit of 3.0×10^{-9} at the 90% confidence level on the branching ratio. The result improves the previous limit by an order of magnitude.

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1. Introduction

The rare kaon decay $K_L^0 \to \pi^0\nu\bar{\nu}$ is one of the best modes to search for new physics. This is a flavor-changing neutral current process and is highly suppressed in the SM. The branching ratio of $K_L^0 \to \pi^0\nu\bar{\nu}$ is predicted to be 3.0×10^{-11} in the SM [1]. Furthermore, the theoretical uncertainty is only a few percent. We may observe small effects from new physics by the measurement of the branching ratio. Several theoretical models of new physics predict larger branching ratios than that of the SM prediction [2, 3]. The current upper limit on this decay is 2.6×10^{-8} at the 90% confidence level set by the KEK E391a experiment [4].

The KOTO experiment at the J-PARC Main Ring accelerator aims to observe the $K_L^0 \to \pi^0\nu\bar{\nu}$ decay. We took the first physics data in 2013 for 100 hours. One event was observed in the signal region with the expectation of 0.34 ± 0.16 background events. An upper limit of 5.1×10^{-8} was set for the $K_L^0 \to \pi^0\nu\bar{\nu}$ branching ratio at the 90% confidence level [5]. After the 2013 run, we improved the detector to suppress background events. We resumed data taking in 2015 and collected the data 20 times larger than 2013. In this paper, results from the analysis are reported.

2. Experiment

A 30-GeV proton beam is delivered from the Main Ring to the hall of J-PARC Hadron Experimental Facility every 6 seconds with a 2-second duration, and struck a 66-mm-long gold target. The "KL beam line" consisting of two collimators, a sweeping magnet, and a lead photon absorber is located along the 16 degree line from the primary proton beam.

A cross-sectional side view of the KOTO detector is shown in Fig. 1. The KOTO detector has an electromagnetic calorimeter made of 2716 undoped CsI crystals to measure energies and positions of two photons from the π^0 decay. A set of plastic scintillators named "Charged Veto(CV)" is located in front of the calorimeter. Two large lead-scintillator sandwich shower counters called "Main Barrel (MB)" and "Front Barrel (FB)" cover the barrel region of the vacuum tank. A photon veto detector called the "Neutron Collar Counter (NCC)" is located inside FB to separate the decay region from the upstream region. A series of veto counters called the "Collar Counters (CCs)" are placed along the beam axis to detect particles escaping to the beam direction. At the downstream end of the detector, "Beam Hole" veto counters are located in the beam.

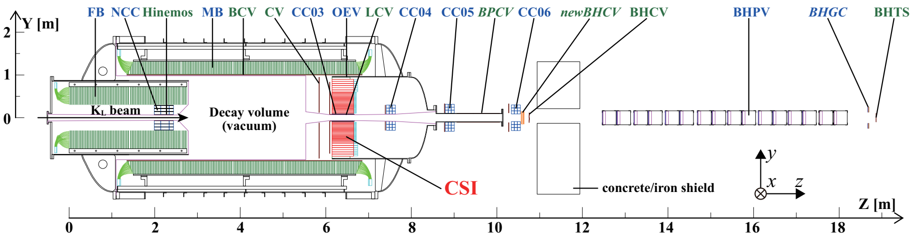

Figure 1: Cross-sectional side view of the KOTO detector. The K_L^0 beam comes in from the left hand side. Also shown is the coordinate system used in this paper: x is the horizontal, y is the vertical, and z is the beam directions. The origin of the coordinate is set at the upstream end of FB.

3. Analysis of the 2015 data

The analysis method is the same as in the first physics run. The decay position of the π^0 , Z_{vex}, is reconstructed along the beam axis, assuming the invariant mass of the two photons equals to the π^0 mass. We require a finite transverse momentum to the signal events because neutrinos should have carried away a finite transverse momentum. In addition, we require hermetic veto counters surrounding the decay region not to have any activities in time and make sure that no other particles than two photons exist in the final state of the decay.

The most serious background source in the first physics run was that neutrons in the beam halo hit the CsI calorimeter directly. The single neutron could make two clusters in the calorimeter through several hadronic interactions. To suppress the halo neutron background events, we studied hadron clusters by using special data. A 10-mm-thick aluminum disk was inserted into the beam to scatter neutrons into the calorimeter. We developed new selection criteria to separate the electromagnetic clusters from the hadron clusters by using a neural network technique and by calculating a likelihood ratio based on fitting parameters to the waveforms for CsI readouts. These new cuts can reduce the number of hadron cluster events by an order of magnitude.

In the 2015 data analysis , we noticed a new background source called the "CV-η background". This background is caused by halo neutrons hitting CV and producing η's. To reduce CV-η events, we developed a new cut to check consistency of the cluster shapes in the assumption that they come from the $\eta \to 2\gamma$ decay at CV. With this cut, the CV-η background was reduced by a factor of 10 with a 90% signal efficiency.

Owing to detector upgrades after the first physics run, we were able to achieve enough suppression for kaon decay backgrounds. The background events were suppressed to be an acceptable level, as shown in Table 1 .

Background source	The number of background events
Halo neutron hitting CSI	0.24 ± 0.17
Halo neutron hitting upstream detectors	0.04 ± 0.03
η background	0.03 ± 0.02
$K_L^0 \to \pi^+ \pi^- \pi^0$	0.03 ± 0.02
$K_L^0 \to 2\pi^0$	0.05 ± 0.02
$K_L^0 \to 3\pi^0$	0.02 ± 0.02
other BG sources	0.02 ± 0.02
Sum	0.40 ± 0.18

Table 1: Estimated numbers of background events in the signal region.

4. Result

After determining all the selection criteria, we examined the signal region and observed no candidates, as shown in Fig. 2. By using the simultaneously-measured $K_L^0 \to 2\pi^0$ events as a normalization mode, the single event sensitivity for the $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay was evaluated to be

1.3×10^{-9}. An upper limit on the $K_L^0 \to \pi^0 \nu \bar{\nu}$ branching ratio was set to be 3.0×10^{-9} at the 90% confidence level, based on Poisson statistics. The result improves the previous limit by an order of magnitude.

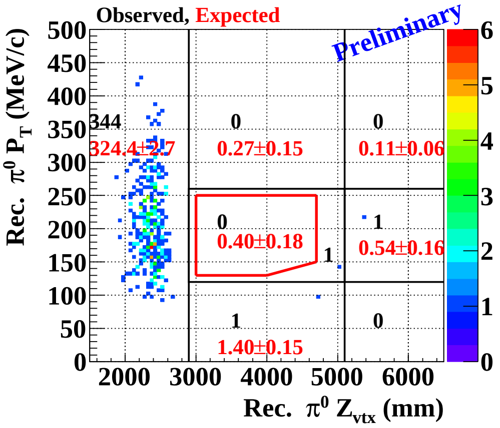

Figure 2: Scatter plot of reconstructed P_T vs Z_{vex} after imposing all selection criteria. The region inside of the red lines is the signal region. The numbers in black show the number of observed events, and the numbers in red show the number of expected background events.

5. Prospect

After 2015, we have collected 1.5 times more physics data and 10 times more neutron data than the data used in 2015 data analysis. We would be able to reach the sensitivity of 5.0^{-10} by using all data including 2015. For the reduction of background events, we will develop more powerful cuts for neutron rejection by using neutron samples and by using a new analysis technique like deep learning.

From the summer of 2018, we upgrade the detector to achieve further background suppression. We will add MPPCs to the upstream end of the calorimeter to get information on the shower development from timing difference between upstream and downstream ends. By using this information, we will reduce neutron events further by a factor of 10. The beam power will increase from 50kW to 90kW gradually, after installing a new production target to the Hadron Experimental Facility in 2019.

References

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