PROCEEDINGS OF SCIENCE

KOTO Status and Prospect

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The KOTO experiment at the J-PARC 30GeV Main Ring aims to observe the $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay. This decay, which directly breaks the CP symmetry, is highly suppressed in the Standard Model (SM), and has small theoretical uncertainties, is sensitive to new physics beyond the SM. The KOTO experiment has been accumulating physics data since 2013 with several detector and DAQ upgrades. We are finalizing the analysis of the dataset taken in 2016-2018. The status of the 2016-2018 data analysis is reported in this paper.

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1. Introduction

The asymmetry between matter and antimatter in the universe is one of the big mysteries in particle physics. One key ingredient to solve the mystery is CP violation, which is explained in the standard model (SM) by the complex phase η of the Cabibbo-Kobayashi-Maskawa matrix. However, the measured value of η is too small to explain the asymmetry observed in the universe. New sources of CP violation are expected in new physics beyond the SM.

The rare kaon decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ is one of the most sensitive probes to search for new physics. This decay directly violates the CP symmetry. It's branching ratio is highly suppressed in the SM and predicted to be 3.0×10^{-11}[1]. The theoretical uncertainty on this decay is only a few percent. Thus, small effects from new physics can be observed as a discrepancy between the measured and predicted branching ratio. Several theoretical models of new physics predict larger branching ratios than that of the SM prediction[2, 3].

The KOTO experiment at the J-PARC Main Ring accelerator aims to observe the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ decay and has been accumulating physics data since 2013 with several detector and DAQ upgrades. We had set the most stringent upper limit on the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ brancing ratio to be 3.0×10^{-9} at the 90% confidence level with the dataset taken in 2015[4]. We are finalizing the analysis with the dataset taken in 2016-2018. The status of the 2016-2018 data analysis is reported in the paper.

2. Experiment

Protons are accelerated up to 30 GeV in the Main Ring and impinged on the 66-mm-long gold target located at the Hadron Experimental Facility. The kaons produced in the target and extracted the 16 degree angle from the primary proton beam through the "KL beam line" consisting of two collimators, a sweeping magnet, and a lead photon absorber.

A cross-sectional side view of the KOTO detector is shown in Fig. 1. The signature of the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ decay is "two photons and nothing". The detector consists of an electromagnetic calorimeter to detect the two photons and hermetic veto counters surrounding the decay region to confirm that there are no other detectable particles. The electromagnetic calorimeter consists of 2716 CsI crystals that have a length of 50 cm with a cross-section of 2.5×2.5 cm^2 (5×5 cm^2) inside (outside) the central 1.2×1.2 m^2 region. In front of the calorimeter, two layers of scintillating counters named "Charged Veto(CV)" are located to identify charged particles. The decay volume is covered by two large lead-scintillator sandwich shower counters called "Main Barrel (MB)" and "Front Barrel (FB)". A photon veto detector called the "Neutron Collar Counter (NCC)" is located inside FB to prevent particles generated at the upstream region of the decay volume from directly hitting the calorimeter. A series of veto counters called the "Collar Counters (CCs)" are placed along the beam axis to catch particles escaping to the beam direction. At the downstream end of the detector, "Beam Hole" veto counters are located in the beam. All the signals from the counters are digitized with custom ADC module every 2 ns for in-beam detectors and 8 ns for other detectors, respectively.

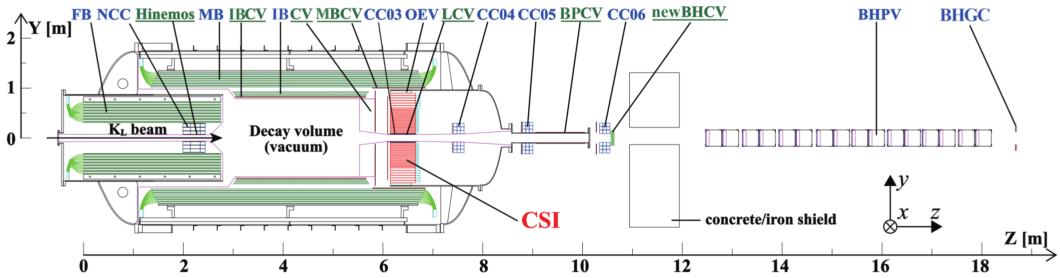

Figure 1: Cross-sectional side view of the KOTO detector. The K_L^0 beam comes in from the left hand side. Also shown is the coordinate system used in this paper: x is the horizontal, y is the vertical, and z is the beam directions, respectively. The origin of the coordinate is set at the upstream end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

3. Analysis

3.1 Basic strategy

The analysis strategy for the 2016-2018 dataset is basically the same as the previous analysis with the 2015 dataset. The decay position of the π^0 , Z_{vtx}, is reconstructed along the beam axis with the assumption that the invariant mass of the two photons equals to the π^0 mass. A missing transverse momentum is required to be large because neutrinos should have carried away a finite transverse momentum. The hermetic veto counters should not have any activities to confirm that no other detectable particles exist in the final state.

The analysis for the 2016-2018 dataset newly implements two selection criteria (cuts) against the hadron-cluster background, which was the main background source in the previous analysis and is caused by hadron clusters being misidentified as photon clusters in the calorimeter. One is a Convolution Neural Network cut based on the energy and timing information of each CsI crystal. The other is a likelihood-ratio cut based on the templates of the frequency spectrum obtained by performing Fourier Transform on the waveforms of the CsI crystals. Combining these two cuts, the reduction power of O(10^{-6}) has been achieved against the hadron-cluster background.

3.2 Opening the signal box and events inside the signal box

We determined the cuts and opened the signal box in August 2019. The number of K_L^0 's decayed in the signal region was measured with $K_L^0 \to 2\pi^0$ samples to be 2.4×10^{11}. The signal acceptance after imposing all the selection criteria was estimated to be 0.6% from the Monte Carlo (MC) simulation. The single event sensitivity (S.E.S) was estimated to be 6.9×10^{-10}.

We observed four candidate events inside the signal box as shown in Fig 2, while the number of background (BG) events expected inside the signal box was 0.05 ± 0.02. This was reported at the international conference on Kaon Physics 2019[5].

After detailed investigation, we found an incorrect parameter setting which was used to determine hit timing of veto counters. One out of the four candidate events, covered with a red circle in Fig. 2, was rejected after re-processing with the modified setting. In the event, a pulse exist in a veto counter in the on-timing but this pulse was not chosen as a veto signal due to the incorrect parameter. The event covered with a blue circle has overlapped pulses in NCC, and the probability of observing such an event is 2.2%. The other two events in the signal region have no such features.

We also found that the charged kaons ($K^{\pm}$) generated in the collision of a K_L^0 with the downstream collimator could enter the KOTO detector. The π^0 from the $K^{\pm} \to \pi^0 e^{\pm} \nu_e$ decay may have enough transverse momentum to enter the signal box because the kinematical limit on the transverse momentum is 228 MeV/c. If an electron is emitted with a small energy and undetected by veto counters, this decay could be a background. The number of $K^{\pm} \to \pi^0 e^{\pm} \nu_e$ background events expected in the signal box was found to be 0.29. However, this value highly depended on the $K^{\pm}$ flux, which was estimated based on the beam line simulation.

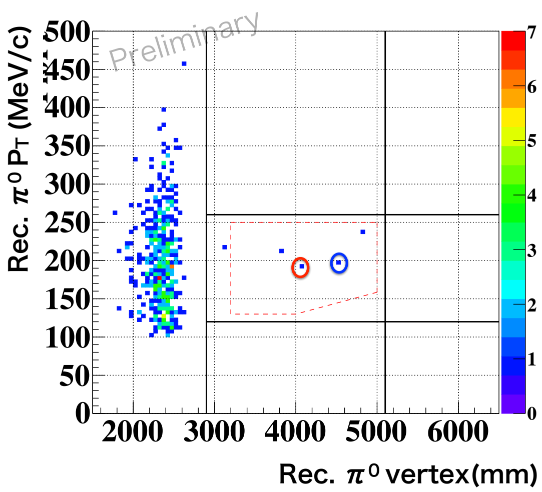

Figure 2: Scatter plot of reconstructed P_T vs Z_{vtx} after imporsing all cuts. The region inside of the red dash lines is the signal region.

3.3 $K^{\pm}$ flux measurement

We carried out a dedicated run in June 2020 to measure the $K^{\pm}$ flux. We collected events with three clusters on the CsI calorimeter to identify the $K^{\pm} \to \pi^0 \pi^{\pm}$ decay. Two photon clusters were selected out of three clusters based on the cluster shapes. The vertex position of the π^0 was reconstructed on the beam axis by assuming that the two photons were from the π^0 decay. The momentum of the $\pi^{\pm}$ was estimated by assuming the momentum balance of the $K^{\pm}$ in the transverse direction. The $K^{\pm} \to \pi^0 \pi^{\pm}$ events were able to be well distinguished from background events by using the reconstructed $K^{\pm}$ mass, as shown in the left plot of Fig 3. By requiring the reconstructed $K^{\pm}$ mass to be close to the $K^{\pm}$ mass, the background events are well suppressed. The signal box for the $K^{\pm}$ events is shown by the blue box in the center plot of Fig 3. The number of events observed in the signal region of the $K^{\pm} \to \pi^0 \pi^{\pm}$ events was three times larger than the number estimated from the MC simulation while the distributions of the reconstructed $K^{\pm}$ mass and momentum were well reproduced by the MC simulation as shown in the right plot of Fig 3.

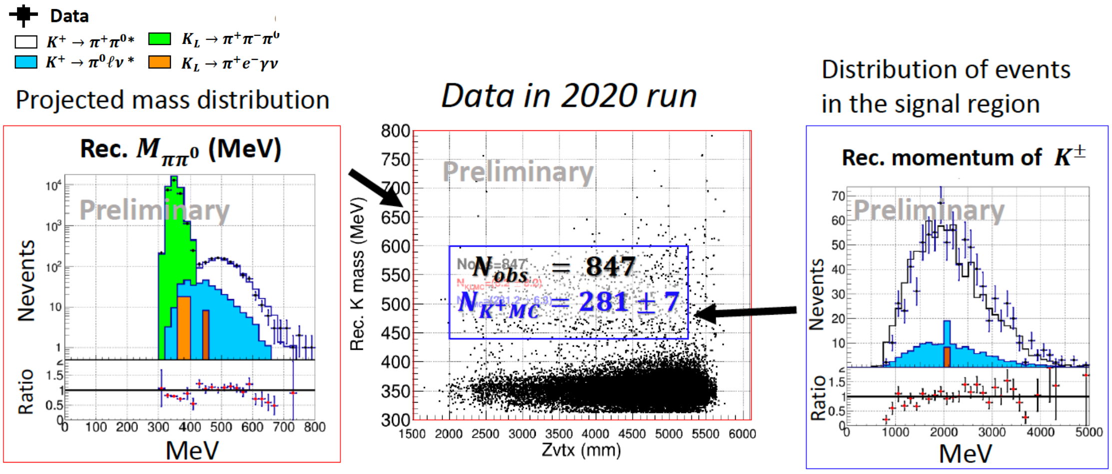

Figure 3: Right plot is the distribution of the reconstructed K$^\pm$ mass. Center plot is the scatter plot of the reconstructed K$^\pm$ mass and the reconstructed K$^\pm$ vertex. The region inside the blue box is the signal region for the $K^\pm \to \pi^0\pi^\pm$ events. Left plot is the distribution of the reconstructed K$^\pm$ momentum for the events inside the signal region.

3.4 Updates of background estimate with $K^\pm$ flux measurement

We updated the estimate of the $K^\pm$ background events based on the results from the $K^\pm$ flux measurement. The number of $K^\pm$ background events expected in the signal region is 0.99 ± 0.28. The main contribution is the $K^\pm \to \pi^0 e^\pm \nu_e$ decay: the number of $K^\pm \to \pi^0 e^\pm \nu_e$ background events is 0.90 ± 0.27. The total number of background events in the singal box is 1.05 ± 0.28. The number of events observed in the signal box, three, is not significantly larger than the total number of background events.

4. Prospect

To detect and reduce $K^\pm$ events, we are developing a new charged-veto counter to be located in the front of the KOTO detector and cover the beam core. In the KOTO detector system, we already installed a prototype counter with a cross section of 84 cm × 95 cm consisting of 1 mm square scintillating fibers before starting the run for the $K^\pm$ flux measurement. It was checked the inefficiency of the prototype module against charged particles by using the $K^\pm \to \pi^0\pi^\pm$ events, as shown in Fig 4. The inefficiency was about 30% due to the limited coverage of the prototype detector, insensitive regions in the fiber, and noise fluctuation. The size of the prototype counter was limited by the size of the vacuum chamber. We will prepare a larger one. The outer cladding of the fiber corresponding to 5.8% of the total area is insensitive. To reduce events that charged particles pass through only the insensitive region and can not be detected, we will tilt the new detector to the beam axis. The scintillation light from the fiber was read out by MPPCs; the location of the MPPCs was close to the beam core and the MPPCs were deteriorated due to irradiation. We will set MPPCs far from the beam core to reduce the effect of irradiation to the MPPCs and reduce the inefficiency of the new counter to be a few percent.

A long shutdown is planed in J-PARC Main Ring in 2021 to upgrade the power supplies of the magnets. We will have beam time for two months before the long shutdown and reach to the S.E.S of 3×10^{-10} by reducing the $K^{\pm}$ background events with the new charged veto counter. The beam power will increase up to 100 kW after the long shutdown. The intensity of the slow extraction beam is not flat in a spill, which make instantaneous rate higher than the flat beam and cause large accidental loss. This time structure in the slow extraction will be better by reducing the ripple noise of the power suplies. We will resume physics data taking from the fall of 2022 and reach to the S.E.S of O(10^{-11}) by three years data taking.

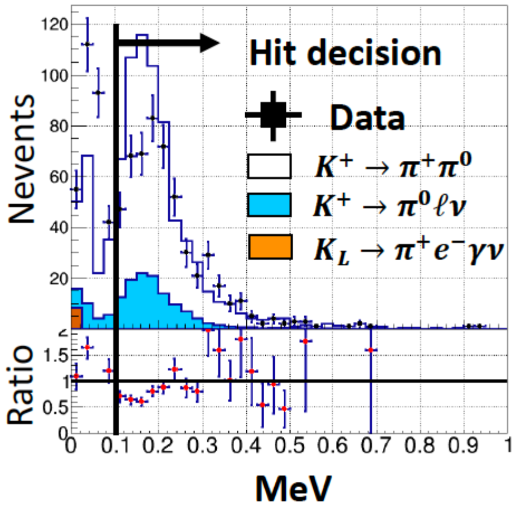

Figure 4: Energy distribution of the prototype detector for the $K^{\pm} \to \pi^0\pi^{\pm}$ events. The dots with bars indicate the data. Each histogram show the simulation results of each mode. To calculate the inefficiency of the detector, the energy threshold of 0.1 MeV indicating by the black line in the plot is required to veto the events. The inefficiency is defined as the ratio of the number of total events and the events in the left side of the black line.

5. Summary

The KOTO experiment studies the rare decay $K_L^0 \to \pi^0\nu\bar{\nu}$ at J-PARC. We are finalizing the analysis with the dataset taken in 2016-2018. We determined the cuts and opened the signal box in August 2019. After the detailed investigation, we found one out of four candidates was due to an incorrect parameter setting related timing calculation. We also found $K^{\pm}$ could be a serious background source. After measuring the $K^{\pm}$ flux, the number of $K^{\pm}$ background events was estimated to be 0.90 ± 0.27. The number of events observed in the signal box, three, is not significantly larger than the total number of background events estimated to be 1.05 ± 0.28.

We are developing a new charged veto counter to reduce the $K^{\pm}$ background events. We will take new data with the new counter and reach to the SES of O(10^{-11}) in a timely manner.

The analysis for the 2016-2018 dataset had been finalized and we submitted the results on the arXiv in December 2020[6].

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