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Status of the KOTO experiment to search for kaon rare decays

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The $K_L \to \pi^0 \nu\bar{\nu}$ decay is searched for in the KOTO experiment. In the analysis of 2016-2018 data, we found new background sources, a charged kaon decay and a beam-halo K_L decay. In the analysis of 2020 data, we show the reduction of the former dominant backgrounds. We hope we will finalize the analysis after evaluating systematic uncertainty on the photon inefficiency due to photonuclear interaction. In the future, we hope we will move to the KOTO II experiment to gain higher sensitivity.

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1. $K_L \to \pi^0 \nu\bar{\nu}$

The decay $K_L \to \pi^0 \nu\bar{\nu}$ is a FCNC process. The branching ratio is $(2.94 \pm 0.15) \times 10^{-11}$ in the Standard Model (SM) [1]. It is sensitive to new physics beyond the SM due to the accurate and suppressed SM contribution.

2. KOTO experiment

The $K_L \to \pi^0 \nu\bar{\nu}$ decay is searched for at the J-PARC KOTO experiment [2]. The current best upper limit of the branching ratio, 3×10^{-9} at the 90% confidence level, was obtained with the data taken in 2015 [3]. Three candidate events were observed with the expected number of background events 1.22 ± 0.26 at the single event sensitivity of 7.2×10^{-10} in the analysis of the data collected in 2016-2018 [4]. The data collected in 2019-2021 are under analysis [5].

Protons of 30 GeV from J-PARC hit the gold target, and secondary particles including K_L are produced. The KL beam line 20-m long from the target prepares a neutral beam in a solid angle of 7.8 μsr with two collimators, while charged particles are swept out with a magnet and short-lived particles decay out in the beam line. The KOTO detector (figure 1) starts at 21.5 m from the target, where the beam size is 8 cm × 8 cm.

The z-axis points the downstream on the beam line with the origin at the start of the detector. The y-axis points upwards, and the x-axis follows the right-handed system.

The signature of the $K_L \to \pi^0 \nu\bar{\nu}$ decay is “two photons with no other detectable particles”. The “two photons” are detected with a calorimeter (CSI in figure 1), and “no other detectable particles” are ensured with all the sub-detectors. The vertex position of the π^0 is reconstructed from the two photons detected at the calorimeter, assuming the vertex on the z-axis and the invariant mass to be the nominal π^0 mass. The z-vertex (Z_{vtx}) and the transverse momentum (P_{t}) of the π^0 are obtained, and are used to define the signal region.

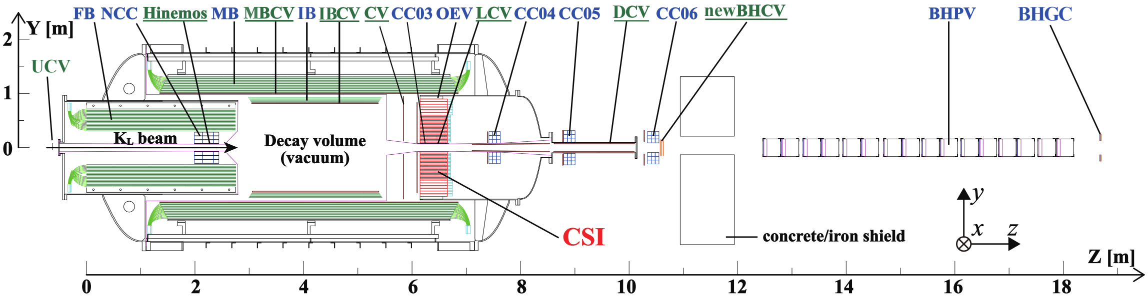

Figure 1: The KOTO detector in 2021. The UCV was not in 2016-2018. A BPCV was in 2016-2018 instead of the DCV.

2.1 Results of analysis for 2016-2018 data

The events after applying all the event selections except for P_{t} and Z_{vtx} are shown in figure 2, and the number of background events in the signal region are summarized in Table. 1 [4]. The dominant backgrounds are $K^{\pm}$ and $K_L \to 2\gamma$ (beam halo).

The $K^{\pm}$ is generated from K_L hitting the collimator downstream of the magnet in the beam line. The flux of $K^{\pm}$ at the entrance of the detector is 2.6×10^{-5} of the K_L flux. The $K^{\pm} \to \pi^0 e^{\pm} \nu$ decay is the dominant source of the $K^{\pm}$ background, where $e^{\pm}$ is missed due to the inefficiency of the detector.

The beam-halo K_L is generated from a scattering of K_L on the inner surface of the collimator. This becomes a background due to higher P_t of the π^0 reconstructed from two photons of the beam-halo $K_L \to 2\gamma$.

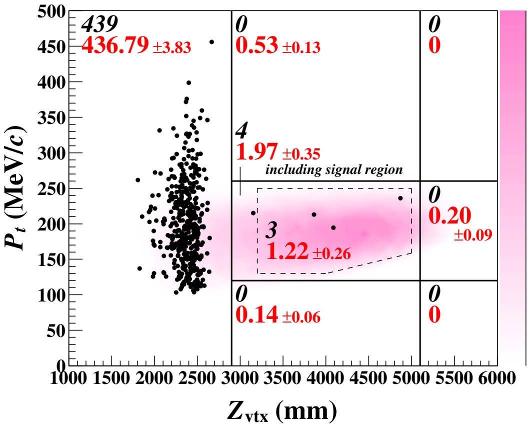

Figure 2: Distribution of events after imposing all the event selections except for $P_{\rm t}$ and $Z_{\rm vtx}$ for the 2016-2018 data analysis. The region surrounded by dotted lines is the signal region. The black dots represent observed events, and the shaded contour indicates the $K_L \to \pi^0 \nu \bar{\nu}$ distribution from the MC simulation. The black italic (red regular) numbers indicate the number of observed (background) events [4].

Table 1: Summary of the numbers of background events for the 2016-2018 data analysis with a central value estimate [4].

source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07
	Other K_L decays	0.005 ± 0.005
$K^{\pm}$		0.87 ± 0.25
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
total		1.22 ± 0.26

2.2 Status of analysis for 2021 data

The KOTO detector was upgraded from the 2016-2018 condition. Plastic scintillators with WLS fibers were installed in 2019 on the inner surface of the downstream beam pipe as the DCV. The DCV efficiently reduces the $K_L \to \pi^+ \pi^- \pi^0$ background, and the signal region was widened in the analysis of 2021 data. The UCV is a single-layer plane of 0.5-mm square scintillating fibers with a tilting angle of 25° [6] as shown in figure 3. It was installed in the beam at the upstream region of the detector in 2020 as a charged particle detector to reduce $K^{\pm}$ background. The inefficiency of UCV for $K^{\pm}$ was evaluated to be $(8.0^{+1.1}_{-3.0})\%$ from control samples with $K^{\pm} \to \pi^{\pm}\pi^{0}$ decay. The number of $K^{\pm}$ background events was evaluated with this inefficiency. Scattering of K_L in the UCV generates "scattered K_L", and it contributes to the background in the same way as in halo $K_L \to 2\gamma$. The halo $K_L \to 2\gamma$ and the scattered $K_L \to 2\gamma$ are reduced with a cluster shape of γ in the calorimeter and a multivariate analysis on the reconstructed π^0 properties. A preliminary analysis gives a clean event distribution around the blinded region with the single event sensitivity of 7.9×10^{-10} as shown in figure 4. The preliminary number of background events are summarized in Table. 2. The former dominant backgrounds from $K^{\pm}$ and beam-halo $K_L \to 2\gamma$ are well suppressed. In this analysis, $K_L \to \pi^0\pi^0$ background becomes dominant. This was evaluated with a simulation with Geant4, and the number of this background events increased due to the change of the Geant4 version. We found that the cause was the change in the model of photonuclear interaction. This increased the photon inefficiency of the barrel couters. In order to finalize the analysis, we are trying to evaluate the photon inefficiency with data.

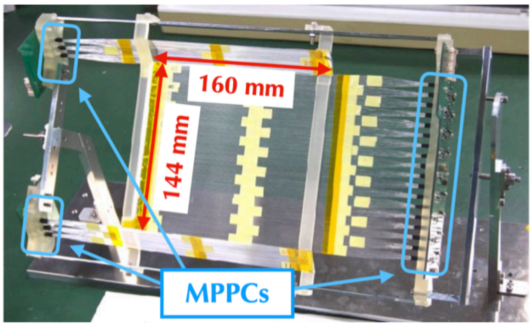

Figure 3: UCV. [6]

Table 2: Number of background evaluated in the analysis on 2020 data (preliminary) [5].

source	Number of events
$K_L \to 2\pi^0$	0.141 ± 0.059
$K^{\pm}$	$0.043^{+0.016}_{-0.022}$
Hadron cluster	0.042 ± 0.007
Halo $K_L \to 2\gamma$	0.013 ± 0.006
Scattered $K_L \to 2\gamma$	0.025 ± 0.010
CV η	0.023 ± 0.01
Upstream π^0	0.02 ± 0.02
$K_L \to \pi^+\pi^-\pi^0$	0.019 ± 0.019
total	$0.325^{+0.069}_{-0.070}$

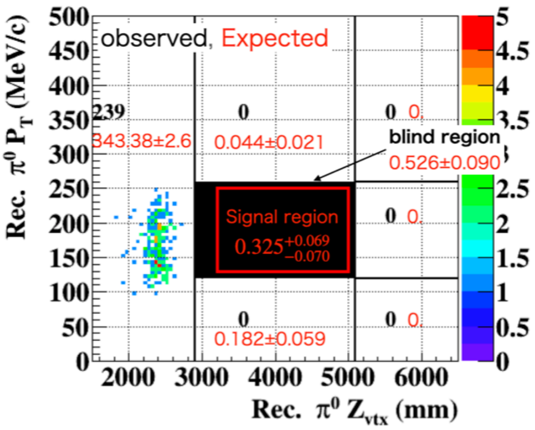

Figure 4: Distributuion of events after imposing all the event selections except for P_t and Z_{vtx} for the 2021 data analysis (preliminary). The region surrounded by red lines is the signal region, and the black filled region is blinded. The color contour represent observed events, The black (red) numbers indicate the number of observed (background) events [5].

3. KOTO II

For the branching ratio of $K_L \to \pi^0 \nu\overline{\nu}$, the sensitiivty of the KOTO experiment will reach below 10^{-10} in several years, and will be saturated. Therefore, we are planning a next-generation experiment, KOTO II to have several tens of signal events aiming at the measurement of the branching ratio.

The hadron experimental facility at J-PARC is planned to be extended with a second production target. We plan to have a new beam line with the extraction angle of 5°, which is smaller than the current 16°. This gives larger flux and harder momentum distribtuion of K_L. We plan to have the KOTO II detector behaind the primary proton dump to realize the 5° extraction angle. The KOTO II detector is designed to have 3-m diameter calorimeter and 12-m long decay region. We allow a loose event selections with the singal-to-background ratio of 0.6 due to higher statistics. These give 190 times larger signal efficiency compared to the current one..

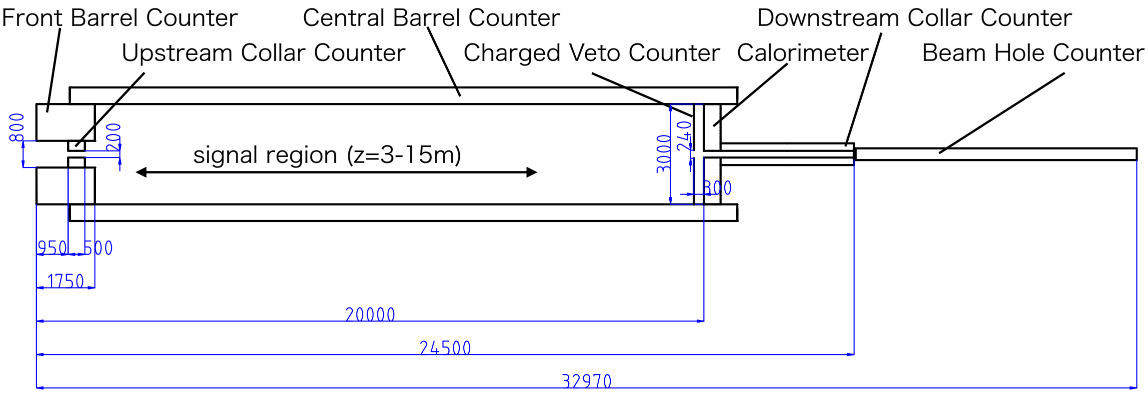

Figure 5: Conceptual design of the KOTO II detector. [7]

In KOTO II, the signal distributions is shown in figure 6(left). The distribution of the dominat background $K_L \to \pi^0\pi^0$ is shown in figure 6(right). In total, 35 signal events from the SM and 56 events from the backgrounds are expected for the continuous running time of 3×10^7 s. It gives 4.7-σ discovery of $K_L \to \pi^0\nu\bar{\nu}$ and 27% measurements of the branching ratio. Observing 110 events gives a 90% indication of new physics, and observing 56 events gives approximately 5-σ exclusion of the SM [7].

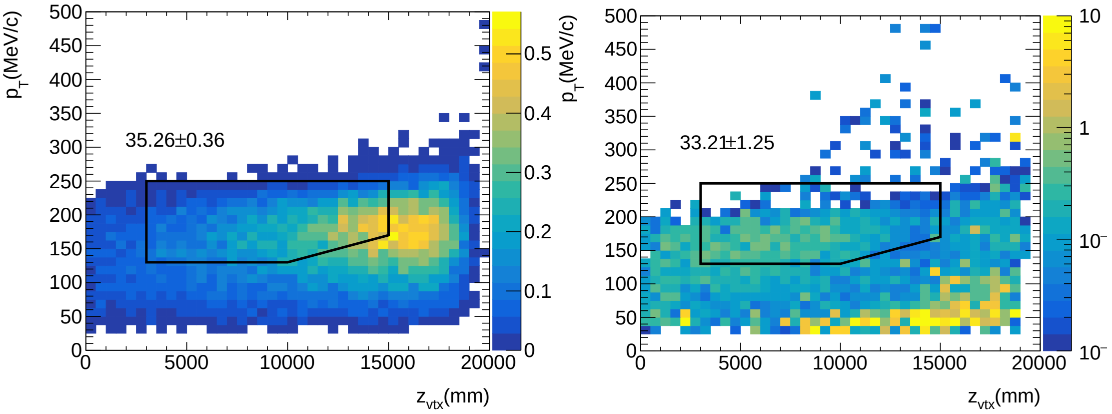

Figure 6: Expected distributions of $K_L \to \pi^0\nu\bar{\nu}$ (left) and $K_L \to \pi^0\pi^0$ (right)) [7]

4. Conclusion

We shows the reduction of the former dominant backgrounds, $K^\pm$ and beam-halo $K_L \to 2\gamma$, with the analysis of 2021 data. We have uncertainty on the number of $K_L \to 2\pi^0$ background events due to the modeling of photonuclear interactions in Geant4. We are trying to evaluate the inefficiency with the data to finalize the analysis. We hope we will move to KOTO II to gain higher sensitivity in several years..

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