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# Status and future prospects for rare kaon decay measurements at KOTO and KOTO II

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The KOTO experiment at J-PARC searches for the rare decay of the neutral kaon, $K_L \to \pi^0\nu\bar{\nu}$. The $K_L \to \pi^0\nu\bar{\nu}$ decay in the standard model is highly suppressed, and its branching ratio is predicted to be $3 \times 10^{-11}$ with a small theoretical uncertainty. The analysis of the $K_L \to \pi^0\nu\bar{\nu}$ search based on data collected in 2021 set the most stringent upper limit on the branching ratio as $2.2 \times 10^{-9}$ at the 90% confidence level. The KOTO experiment has further accumulated data since 2023 with upgraded hardware and data acquisition systems. With several years of data collection in the future, we aim to achieve a single event sensitivity better than $1 \times 10^{-10}$. A next-generation experiment, KOTO II, is also under discussion toward measurements of the branching ratio of $K_L \to \pi^0\nu\bar{\nu}$. In this report, the latest status of the analysis for the $K_L \to \pi^0\nu\bar{\nu}$ search at KOTO and a current design for the KOTO II experiment will be described.

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## 1. Introduction

The $K_L \to \pi^0\nu\bar{\nu}$ decay is the ultra-rare decay mode of the neutral kaon, which directly violates the CP symmetry. This decay is sensitive to new physics because the Standard Model (SM) contribution is highly suppressed and is accurately predicted. The branching ratio of $K_L \to \pi^0\nu\bar{\nu}$ is calculated as $(2.94 \pm 0.14) \times 10^{-11}$ [1]. The uncertainties mostly arise from parameters of the CKM matrix element while intrinsic theory uncertainties amount to only a few percent [2].

The current best upper limit for the branching ratio was set as $2.2 \times 10^{-9}$ at the 90% confidence level (C.L.) by the KOTO experiment based on data collected in 2021 [3]. An indirect limit derived from $K^+ \to \pi^+\nu\bar{\nu}$ via the Grossman-Nir bound [4] can be expressed as

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \lesssim 4.3 \cdot \mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}), \tag{1}$$

where $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ and $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ represent the branching ratios of $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$, respectively. The branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ was measured by the NA62 experiment at CERN [5], and the corresponding limit on the $K_L \to \pi^0\nu\bar{\nu}$ branching ratio is approximately $7.1 \times 10^{-10}$ with the $1\sigma$ error of the measurement taken into account. Figure 1 illustrates the current experimental constraints. Although the current indirect limit is better than the direct limit given by KOTO, there is a chance for more than one order of magnitude enhancement in the $K_L \to \pi^0\nu\bar{\nu}$ branching ratio.

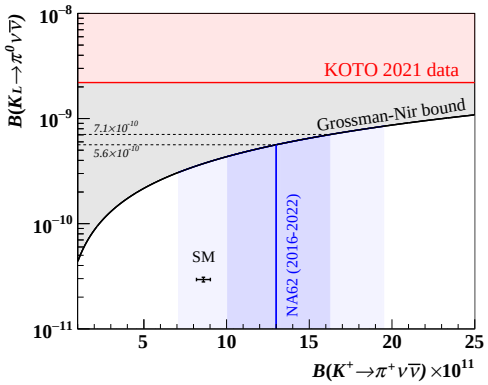


**Figure 1:** Current experimental constraints on $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$. The red region was excluded at the 90% C.L. by the KOTO experiment [3]. The blue regions are the results of the measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio by the NA62 experiment based on data collected from 2016 to 2022 [5]. The blue line represents the central value and the dark blue (light blue) region represents the $1\sigma$ ($2\sigma$) range. The gray region corresponds to the Grossman-Nir bound. The SM prediction in the figure is quoted from [1].

## 2. KOTO experiment

### 2.1 Experimental apparatus and reconstruction

The KOTO experiment [6] is conducted at the Japan Proton Accelerator Research Complex (J-PARC) [7]. The J-PARC main ring delivers 30-GeV protons to the production target (T1 target)

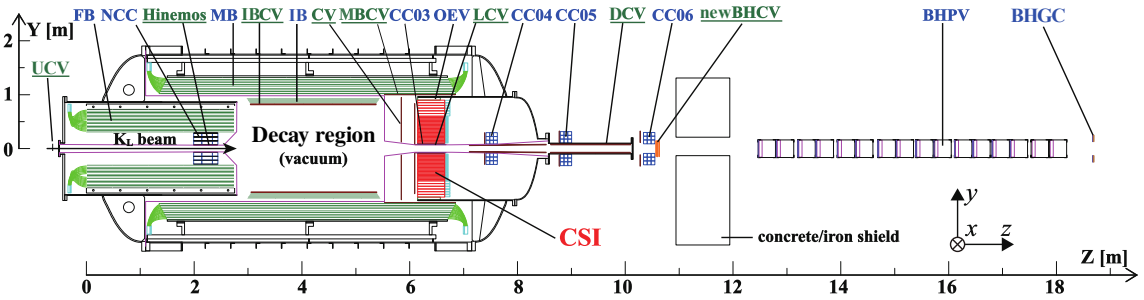


**Figure 2:** Cross-sectional view of the KOTO detector. Detector components with their abbreviated names written in blue (in green and underlined) are photon (charged-particle) veto counters.

placed at the Hadron Experimental Facility (HEF). Secondary particles produced at the target are guided to the KOTO detector through a 20-m-long beamline. The beamline is located at a production angle of 16° with respect to the primary proton beamline. Charged particles are removed by a sweeping magnet located between two collimators, and short-lived particles decay out in the beamline. Neutral particles including photons, neutrons, and $K_L$'s remain at the exit of the beamline (beam exit). The cross-sectional size of the neutral beam at the beam exit is 8 cm × 8 cm. The $K_L$ momentum peaks at 1.4 GeV/$c$ and the flux is $2.1 \times 10^{-7}$ $K_L$'s per proton on target (POT).

Figure 2 shows the schematic view of the KOTO detector. The key of signal identification is detection of two photons from the $\pi^0$ decay without any other detectable particles. Thus, the KOTO detector has a 1.9-m-diameter electromagnetic calorimeter (denoted as CSI in fig. 2) to measure energies and hit positions of the two photons while the other sub-detectors (veto detectors) surround the decay region to ensure the absence of extra detectable particles.

The $\pi^0 \to 2\gamma$ decay vertex ($Z_{\text{vtx}}$) is reconstructed with the assumption that the decay occurs on the beam axis and the two-photon invariant mass has the nominal $\pi^0$ mass. The transverse momentum of the reconstructed $\pi^0$ ($P_t$) tends to be large due to the missing neutrinos. The signal region is defined on the $P_t$ vs $Z_{\text{vtx}}$ plane and is blinded until event selection criteria are determined.

### 2.2 Recent status of data collection and analysis

The KOTO experiment has continued collecting data since 2023 after the long-shutdown period for the MR power supply system. A part of the KOTO detector and the beamline components was upgraded to improve the rejection power against background events. One of the background sources in the $K_L \to \pi^0\nu\bar{\nu}$ analysis in KOTO is $K^\pm$ contaminating the neutral beam. The $K^\pm$'s are generated at the downstream collimator due to charge exchange of $K_L$'s hitting the wall of the collimator. Once the $K^\pm \to \pi^0 e^\pm \nu$ decay occurs in the decay region, such events could be background if two photons from the $\pi^0$ decay hit the electromagnetic calorimeter and $e^\pm$ is not detected. In the previous analysis of the data taken in 2021, the $K^\pm$ background events were reduced by installing a charged-veto counter called Upstream Charged Veto (UCV) at the entrance of the KOTO detector [8]. In order for UCV to be less sensitive to neutral particles in the beam, the detector was composed of 0.5-mm-square scintillating fibers. Using a control sample of $K^\pm$ decays collected during the data-taking in 2021, the $K^\pm$ detection inefficiency was estimated to be $\left(7.8^{+0.6}_{-5.2}\right)\%$, which allowed to reduce the $K^\pm$ background events by a factor of 13 [3].

The rejection power against the $K^{\pm}$ background was improved by the two upgrades: a new UCV and additional magnet in the beamline. A new detector for UCV was developed with a 0.2-mm-thick plastic scintillator film and 12-$\mu$m-thick aluminized mylar, and is hereinafter referred to as film UCV. It was installed in place of the former UCV in 2023. Performance of film UCV was evaluated with beam data taken in 2024. The light yield of 18.5 photoelectrons (p.e.) was obtained and the inefficiency of 0.1% or less was achieved [9]. A permanent magnet was also installed at the downstream end of the downstream collimator to sweep away the $K^{\pm}$'s before they enter the decay volume of the KOTO detector. The magnet has a length of 540 mm along the beam axis and the maximum field strength of 0.9 T. The magnet is expected to reduce the $K^{\pm}$ flux by a factor of 10. These two upgrades made the contribution of the $K^{\pm}$ background negligible.

The data-acquisition system was also upgraded after 2021 [10]. In particular, new types of triggers were introduced to collect various events in the recent data-taking periods. One of the new triggers was motivated to collect a control sample to evaluate inefficiencies of the photon veto detectors. In the previous data analysis, we suffered from a systematic uncertainty of 100 % induced by the lack of statistics of the control sample in the background estimation of the $K_L \to \pi^0\pi^0$ decay [3]. The new trigger was used to collect $K_L \to \pi^0\pi^0\pi^0$ events in which five out of six photons in the final state hit the electromagnetic calorimeter and the remaining photon hits a veto detector. One can reconstruct the momentum of the remaining photon based on kinematic constraints on the $K_L \to \pi^0\pi^0\pi^0$ decay, and evaluate inefficiencies of the photon veto detectors using these events. The systematic uncertainty on the photon veto inefficiency is expected to be reduced to about 10% in the analysis of data collected from April 2024 to June 2025.

From April 2024 to June 2025, a total of $6.6 \times 10^{18}$ POT (preliminary) were collected with the beam power of up to 92 kW. This is twice as much as the statistics of the data collected in 2021. Figure 3 shows the distribution of $P_t$ vs $Z_{\mathrm{vtx}}$ for the data. So far, no events have been observed outside the blind region except for the upstream region which is dominated by the upstream-$\pi^0$ background events [3]. The analysis of quality and stability checks of the data is currently underway.

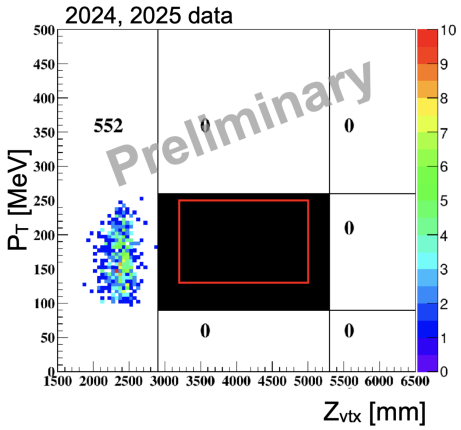


**Figure 3:** Distribution of $P_t$ vs $Z_{\mathrm{vtx}}$ for the data after imposing almost the same event selection criteria as the one used in the previous data analysis [3]. The black region represents the blind region and the red box represents the signal region. The black numbers indicate the number of observed events in each region.

### 2.3 Prospect of KOTO

The KOTO experiment will continue to collect data for several more years. The accelerator beam power is expected to be further increased to about 100 kW in the future. In KOTO, we aim to achieve a single event sensitivity (SES) better than $1 \times 10^{-10}$ with the future dataset.

## 3. KOTO II experiment

A next-generation experiment after the KOTO experiment is currently discussed. The KOTO II experiment [11] is in the design phase towards measurements of the branching ratio of $K_L \to \pi^0 \nu\bar{\nu}$. It is planned to be conducted at the extended HEF [12] with a new beamline and detectors. In the current design, the extended HEF accommodates an additional production target (T2 target) behind the T1 target. A 43-m-long beamline is located behind the T2 target with an extraction angle of 5° with respect to the primary beamline. The smaller extraction angle can produce a $K_L$ beam with a 2 times higher peak momentum and a 2.6 times higher flux compared to KOTO. Figure 4 shows the base design of the KOTO II detector. The detector has a 3-m-diameter calorimeter and a 20-m-long barrel veto detector. The size of the signal region along the beam axis is assumed to be 12 m to obtain large signal acceptance.

Under the assumption of $3 \times 10^7$ s for data taking with 100-kW beam power, we expect to achieve the SES of $8.5 \times 10^{-13}$ and to observe 35 SM signal events with 40 background events. That will result in the discovery of $K_L \to \pi^0 \nu\bar{\nu}$ with a significance of $5.6\sigma$. If the measured branching ratio is deviated from the SM prediction by 40%, it gives an indication of new physics at the 90% C.L.

As for the prospect of KOTO II, the experimental proposal [11] was already submitted to the J-PARC program advisory committee in 2025, and was scientifically approved. Toward full approval of the experiment, more realistic and detailed design of the beamline and the detector is ongoing.

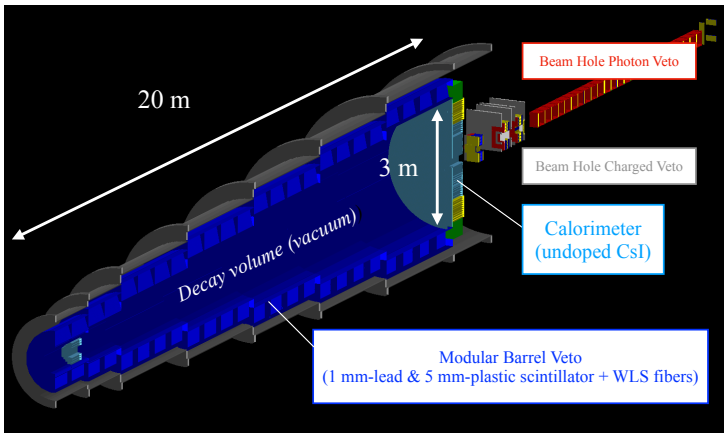


**Figure 4:** Cutaway view of the KOTO II detector with a base design.

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