A future $K_L^0 \to \pi^0 \nu\overline{\nu}$ experiment at J-PARC

Tadashi Nomura[1,2]

[1] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[2] J-PARC Center, Tokai, Ibaraki 319-1195, Japan

E-mail: `tadashi.nomura@kek.jp`

Abstract. A next-generation experiment at J-PARC to measure the branching ratio of $K_L^0 \to \pi^0 \nu\overline{\nu}$ is being considered. The currently-running experiment in the Hadron Experimental Facility of J-PARC, the KOTO experiment, will reach a sensitivity below 10^{-10} in 3–4 years but would take longer time toward the sensitivity predicted by the Standard Model. It is desirable to have a new experiment that can observe $O(100)$ events and measure the branching ratio of $K_L^0 \to \pi^0 \nu\overline{\nu}$. Such an experiment, so-called KOTO step-2, has been discussed as a part of the project of the facility extension. A new beam line with a smaller production angle and a larger detector, accommodated in the extended facility, will provide a higher kaon flux and a larger detection acceptance, and thus brings a better sensitivity. In this paper, a baseline design of the KOTO step-2 and its potential sensitivity are discussed.

1. Introduction

Measurement of the branching ratio of the CP-violating decay $K_L^0 \to \pi^0 \nu\overline{\nu}$ is one of the plausible ways to search for new physics beyond the Standard Model (SM). This decay occurs through the flavor-changing neutral current and is strongly suppressed in the SM. The branching ratio is calculated in the SM with small uncertainties to be $(3.0 \pm 0.3) \times 10^{-11}$ [1]. Precise measurements of the branching ratio therefore could reveal a small deviation from the SM prediction and thus the existence of new physics contribution. The $K_L^0 \to \pi^0 \nu\overline{\nu}$ decay has not been observed so far. The KOTO experiment, the dedicated experiment to search for the $K_L^0 \to \pi^0 \nu\overline{\nu}$ decay at J-PARC Hadron Experimental Facility (HEF), has been running. Based on the data taken in 2015, the experimental upper limit was set to be 3×10^{-9} at the 90% confidence level [2], which is two orders of magnitude above the SM prediction. The single event sensitivity of the data collected in 2016–18 is preliminarily estimated to be 6.9×10^{-10} [3].

The experimental sensitivity depends on the power of the primary proton beam and the accumulated time for data taking. Considering the operation plan of the J-PARC 30 GeV Main Ring (MR) accelerator and the expected running time, and extrapolating from the achieved sensitivity, the KOTO experiment will reach a sensitivity level below 10^{-10} in 3–4 years but would take longer time toward the sensitivity level that corresponds to the SM-predicted branching ratio. It is desirable to plan a new experiment that can observe $O(100)$ SM-predicted events.

An idea of such experiment has already been described in the KOTO proposal in 2006 [4], which we called KOTO step-2. However, the feasibility from the viewpoints of the facility arrangement was not deeply discussed in it. Now, the upgrade of HEF, which aims to expand the capability in nuclear and hadron physics as well as particle physics like KOTO step-2 by extending the experimental hall, is under discussion as one of the next large-scale projects of

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KEK [5]. We are eagerly considering the realization of KOTO step-2 to be accommodated in the early phase of the HEF extension project.

2. Basic concept of KOTO step-2

The experimental sensitivity for a rare K_L^0 decay is determined by the combinations of several factors: the intensity of the primary proton beam, the K_L^0 flux to the experimental area, the detection acceptance for K_L^0 decays, and the running time for data collection. In the design of KOTO step-2, we firstly consider a higher K_L^0 flux and a better detection acceptance as the most important keys.

A 30-GeV proton beam extracted from the J-PARC MR accelerator strikes a target, and secondary neutral particles, including K_L^0s, are lead to the beam line for the experiment. The K_L^0 flux depends on the angle between the primary proton beam and kaon beam line directions (production angle). Figure 1 shows the K_L^0 and neutron yields and the neutron-to-K_L^0 flux ratio as functions of the production angle. To obtain a higher K_L^0 flux, the production angle of 5 degrees is chosen for KOTO step-2, while the angle in the KOTO experiment is 16 degrees. In addition, we consider a thicker production target, a gold rod with its length of 102 mm (one interaction length), while the target used in KOTO is 60 mm long.

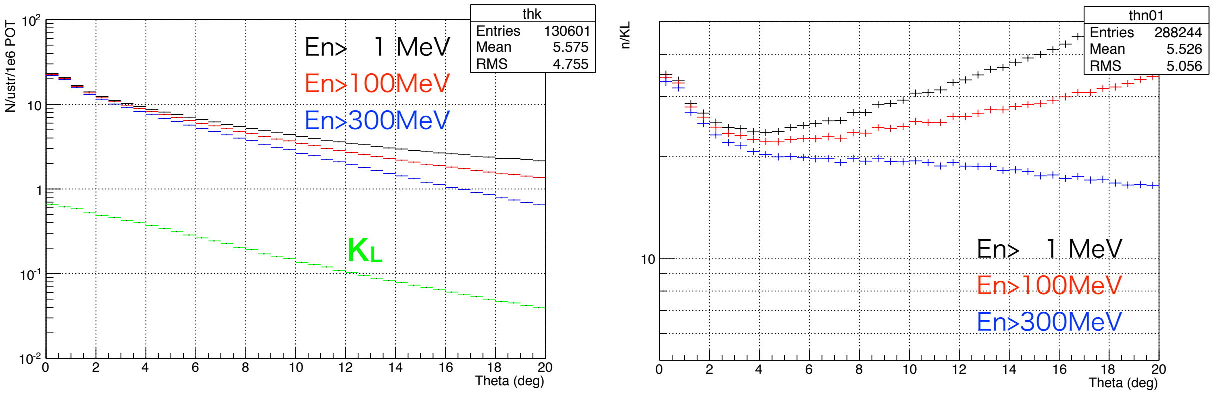

Figure 1. Simulated K_L^0 and neutron yields (left) and their ratio (right) as functions of the production angle. Black, red, and blue points indicate the results when the kinetic energies of neutrons were required to be more than 1, 100, and 300 MeV, respectively.

To obtain a better detection acceptance, a much larger detector than KOTO, as illustrated in Fig. 2, is considered. The basic detector configuration for KOTO step-2 is the same as KOTO.

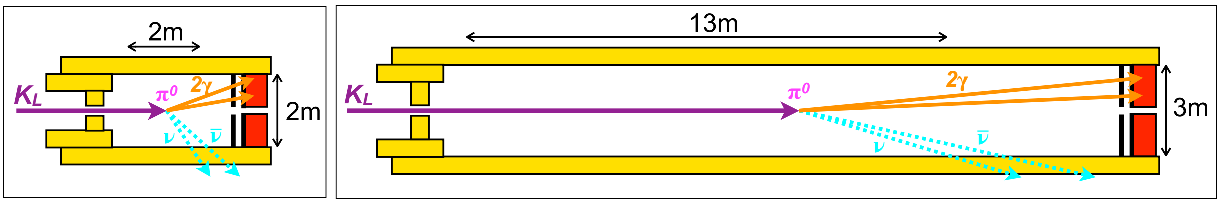

Figure 2. Schematic illustrations of the KOTO detector (left) and a model detector for KOTO step-2 (right). Cross-sectional views of the cylindrical detectors are shown. Red boxes indicate the electromagnetic calorimeter for detecting two photons in the signal, and yellow boxes surrounding the decay region indicate veto detectors. A horizontal dimension line in each figure indicates the length of the fiducial decay region.

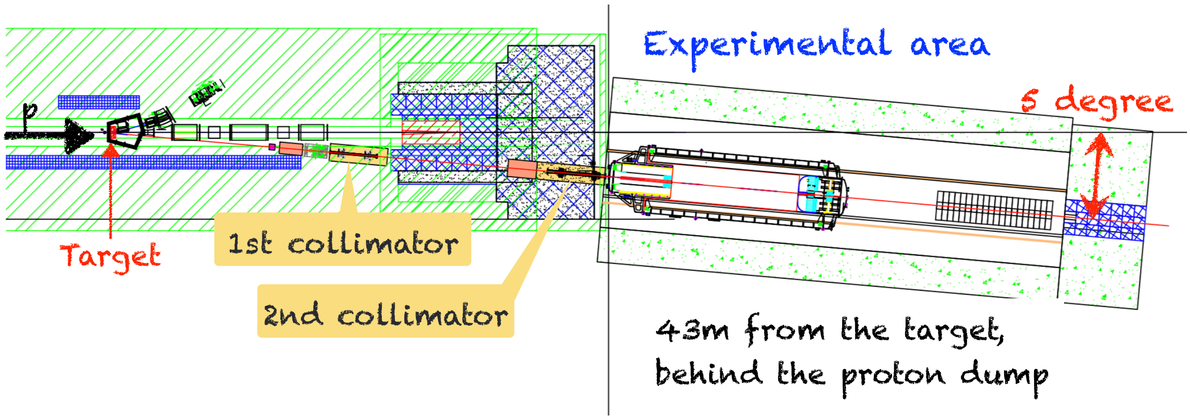

Figure 3. Beam line and detector configuration for KOTO step-2. The detector is located behind the dump for primary protons. The production angle is set to be 5 degree.

The electromagnetic calorimeter at the end-cap is used for detecting two photons from the π^0 in the $K_L^0 \to \pi^0\nu\overline{\nu}$ decay. The veto detectors surrounding the decay region ensure that there are no other particles. The size of the calorimeter is 3 meters in diameter, and the length of the fiducial volume in the decay region is 13 meters; in KOTO, they are 2 meters in diameter and 2 meters in length. A higher K_L^0 momentum is obtained in case of the 5-degree production angle, and thus a longer decay region will be used without losing much detection acceptance by the end-cap calorimeter.

3. Models of the beam line and detector

Figure 3 shows a possible configuration of the beam line and the detector. Table 1 summarizes the assumed parameters for KOTO step-2 in this discussion.

Table 1. Assumed parameters for KOTO step-2, comparing with those for KOTO.

	KOTO step-2	KOTO
Beam power	100 kW*	(51 kW → 100 kW in future)
Target	102-mm-long gold	60-mm-long gold
Production angle	5°	16°
Beam line length	43 m	20 m
Solid angle	4.8 μsr	7.8 μsr
End-cap detector diameter	3 m	2 m
Fiducial decay region length	13 m	2 m
Beam hole on the end-cap	~20 cm sq.	~15 cm sq.

* The beam power of 100 kW corresponds to 2×10^{13} POT/s with 30 GeV protons.

In order to realize the 5-degree direction to the primary beam line, the experimental area should be located behind the beam dump to avoid conflicts with the necessary thickness of radiation shields along the primary beam line. Since the remaining beam after the target must be guided safely to the beam dump, a few magnets should be located between the target and the beam dump. Due to this limitation, the minimum distance from the target to the experimental area is about 43 m. This limits the solid angle of the neutral beam if the beam size at the end-cap detector is required to be reasonably small. In the working model here, the beam size at the end-cap is set to be ±10 cm square.

As the first step, the neutral beam line for KOTO step-2 was designed by following the design principle of the KOTO beam line. It consists of two 5-m-long collimators, one sweeping magnet, and a photon absorber made of lead reducing the photon yield in the beam. The hole of each collimator has a rectangular shape in cross-section, and their gradients along the beam direction were optimized to minimize the particles spreading over the halo region. Figures 4 and 5 show the K_L^0 momentum distribution and the neutron profile at the end-cap calorimeter position, respectively, obtained by our simulation. The K_L^0 momentum spectrum has a peak around 3 GeV/c, and the K_L^0 yield is 2.5 times larger than the observed yield in KOTO. The ratio of the halo neutron yield to the core neutron yield was evaluated to be 1.8×10^{-4}. Here, we define the halo neutrons as neutrons spreading outside of the ±10 cm region at the end-cap detector. The yields of hyperons such as Λ and Ξ, which are potential sources of backgrounds, were found to be small. Note that the design of the beam line has not been fully optimized yet and further improvement are expected.

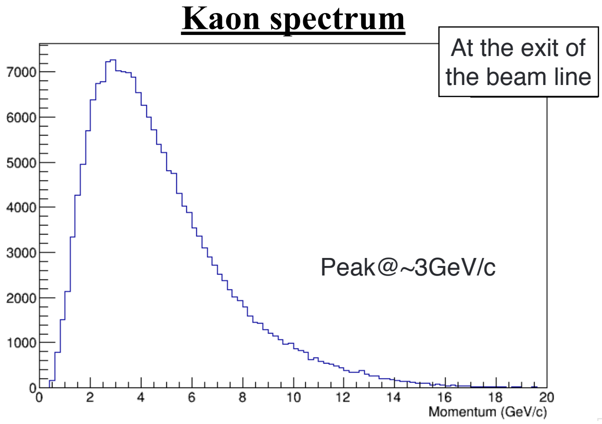

Figure 4. Simulated K_L^0 spectrum.

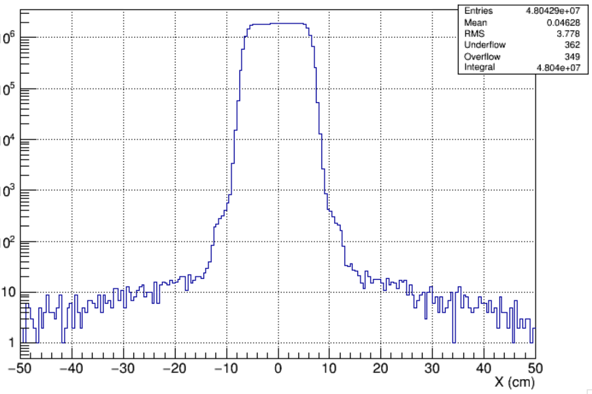

Figure 5. Horizontal neutron profile at the end-cap plane.

Table 2. Expected particle yields estimated by the simulations.

K_L^0		1.1×10^7 / (2×10^{13} POT)
Photon	>10 MeV	5×10^7 / (2×10^{13} POT)
	>100 MeV	1×10^7 / (2×10^{13} POT)
Neutron	>0.1 GeV	3×10^8 / (2×10^{13} POT)
	>1 GeV	2×10^8 / (2×10^{13} POT)

4. Sensitivity and background

By using a fast simulation, the number of expected $K_L^0 \to \pi^0 \nu \bar{\nu}$ signals and various background levels were estimated. Detector responses in the fast simulation were evaluated by using model functions for energy resolutions, detection efficiencies, etc., which were obtained by independent simulations according to the detector type. Here we assume the running time for data collection to be 3×10^7 s collected in three years, with the MR beam power of 100 kW on the target.

Figure 6(a) indicates a scatter plot of the π^0 transverse momentum and the π^0 vertex position for the $K_L^0 \to \pi^0\nu\overline{\nu}$ signals after imposing kinematical selections used in the KOTO experiment. Figures 6$(b)(c)(d)$ show the plots for backgrounds as $K_L^0 \to 2\pi^0$, $K_L^0 \to \pi^+\pi^-\pi^0$, and neutron interactions in the end-cap calorimeter, respectively. The polygons in the figures indicate the signal region. We can expect to observe 60 SM-predicted events with the signal-to-noise ratio of 1. Note that the selection criteria, including the definition of the signal box, are not optimized, and the resultant numbers are only for discussion. Further considerations such as the optimization of the detector arrangement and the evaluation of the signal loss due to accidental hits in the veto detectors are needed in future.

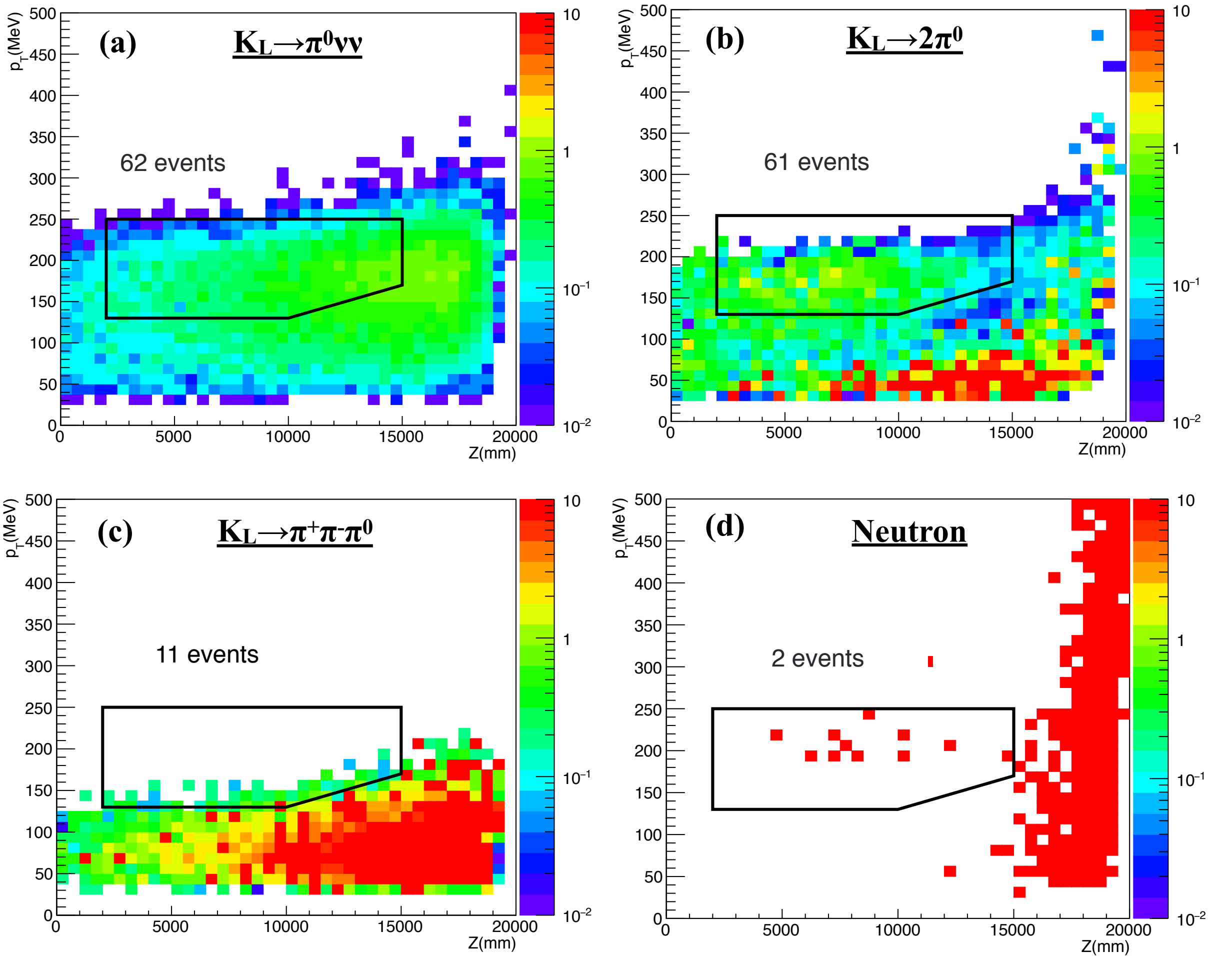

Figure 6. Reconstructed π^0 transverse momentum (P_T) vs π^0 vertex position (Z) after implying selection criteria for (a) the $K_L^0 \to \pi^0\nu\overline{\nu}$ signal, and backgrounds as (b) $K_L^0 \to 2\pi^0$, (c) $K_L^0 \to \pi^+\pi^-\pi^0$, and (d) neutron interactions in the end-cap calorimeter. A polygon in each plot indicates the signal region.

5. Summary and prospect

We are considering a next-generation $K_L^0 \to \pi^0 \nu \overline{\nu}$ experiment at J-PARC, which aims to observe $O(100)$ SM-predicted events. The basic concepts to achieve such sensitivity are to make the beam line with a 5-degree production angle and to use the end-cap electromagnetic calorimeter with a larger diameter of 3 m, and to use a longer decay volume of 13 m. With a working model of the beam line and detector, a preliminary estimation of the sensitivity and backgrounds have been made. Further optimization to improve the performance continues, as well as realistic designs of the beam line and the detector, R&D for the large detector, and so on.

We are also considering new experimental concepts. One of such options is a scheme to detect signals by detectors located at the barrel region of the cylindrical configuration, instead of an end-cap calorimeter. The merit of the configuration is such that it can be extended in the beam direction effectively without losing the acceptance and can provide about 18 times larger acceptance than that in the KOTO experiment with a 10-m-long detector. It would be accommodated in the current KOTO experimental area and thus may be realized independently from the Hadron Hall extension. Although it requires the photon direction measurement, which is technically challenging, we think it is worth considering further as an option and develop the needed/corresponding detectors.

Acknowledgments

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