Reduction of charged kaon background in the KOTO experiment

R Shiraishi

Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

E-mail: shiraishi@champ.hep.sci.osaka-u.ac.jp

Abstract. The KOTO experiment at J-PARC searches for the rare kaon decay $K_L \to \pi^0 \nu \bar{\nu}$. In the analysis of the data collected from 2016 to 2018, the largest background was caused by decays of $K^{\pm}$. To detect $K^{\pm}$ in the beam line, we developed an in-beam charged particle detector in 2020. After installing it in the KOTO detector system, we collected physics data in 2021. Using a control sample of $K^{\pm}$ events, we estimated the inefficiency to be $8.0^{+1.1}_{-3.0}\%$, which reduces the $K^{\pm}$ background by a factor of 13. The number of $K^{\pm}$ background events was suppressed to be $0.043^{+0.016}_{-0.022}$ at the single event sensitivity of 7.9×10^{-10}.

1. Introduction

We study the rare decay of the neutral kaon, $K_L \to \pi^0 \nu \bar{\nu}$, at the J-PARC KOTO experiment. The branching ratio of this decay mode is highly suppressed to be 3×10^{-11} in the standard model (SM) and it is accurately predicted with a small theoretical uncertainty [1]. Thus, this decay mode enables us to search for new physics beyond the SM.

As shown in figure 1, the signature of $K_L \to \pi^0 \nu \bar{\nu}$ is the two photons produced from the π^0 decay without any other detectable particles. To detect this signal, the KOTO detector consists of a Cesium Iodide (CsI) calorimeter and veto detectors surrounding the decay volume.

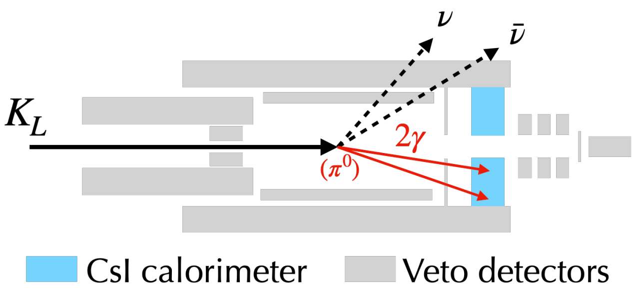

Figure 1. The KOTO detector with the $K_L \to \pi^0 \nu \bar{\nu}$ decay.

2. Charged kaon background

In the analysis of the data collected from 2016 to 2018, we found a new background source which resulted in the largest contribution to the expected number of background events [2]. The new background was caused by decays of $K^{\pm}$ contaminating the neutral beam. Figure 2 shows one of the mechanisms of the $K^{\pm}$ background. $K^{\pm}$ can be produced at the downstream collimator due to charge-exchange interactions of K_L or hadronic interactions of $\pi^{\pm}$ produced from the K_L decay. The ratio of $K^{\pm}$ to K_L flux is 3×10^{-5} at the exit of the beam line. If the $K^{\pm} \to \pi^0 e^{\pm}\nu$ decay occurs in the decay volume, it can become a background, especially in case that the two photons from the π^0 are observed in the calorimeter while the extra $e^{\pm}$ is not detected due to dead material in the veto detectors.

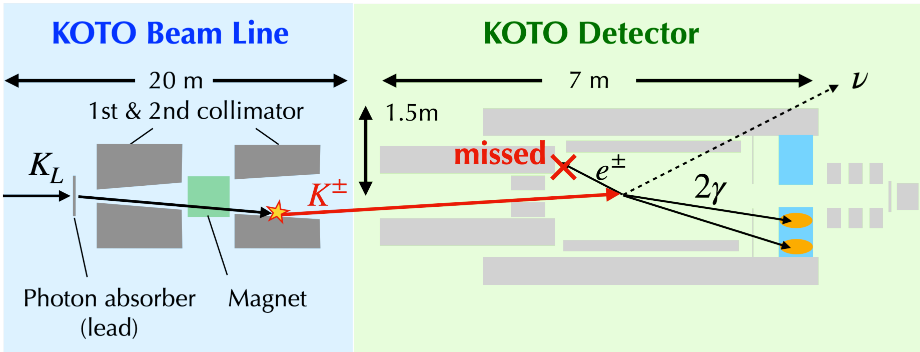

Figure 2. The mechanism of the $K^{\pm}$ background.

3. Upstream Charged Veto (UCV)

In order to reduce the $K^{\pm}$ background, we developed a charged particle detector named Upstream Charged Veto (UCV) in 2020. As shown in figure 3, UCV consists of 0.5-mm square scintillating fibers that are aligned to make structure of a single-layer plane. Signals are read out from the edge of the fibers by silicon photomultipliers called Multi-Pixel Photon Counter (MPPC). We tilted UCV from the plane perpendicular to the beam axis for the following reason. Charged particles do not deposit energy when they pass through the inactive region of the fibers perpendicularly. By tilting UCV, we reduced such events to avoid worsening the efficiency.

We installed UCV at the upstream end of the KOTO detector in 2021.

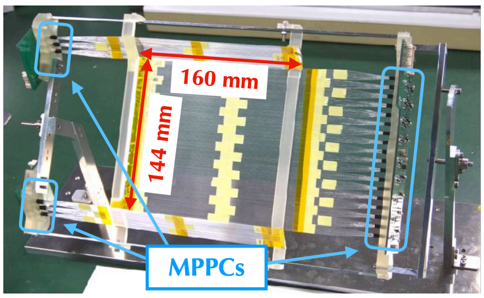

Figure 3. Photograph of UCV.

4. Performance

To evaluate the inefficiency of UCV, we collected a control sample of $K^{\pm} \to \pi^{\pm}\pi^0$ decay events with a dedicated trigger in 2021. This trigger selected events with three clusters in the calorimeter as well as a coincident hit in the charged veto counter located just in front of the calorimeter. The $\pi^0 \to 2\gamma$ decay vertex position (Z_{vtx}) was reconstructed based on the two neutral clusters with an assumption that the π^0 decay occurs on the beam axis. The direction of the $\pi^\pm$ was calculated from the Z_{vtx} and the position of the charged cluster in the calorimeter. Assuming the P_T balance between the π^0 and $\pi^\pm$, the absolute momentum of the $\pi^\pm$ was obtained.

Figure 4 shows reconstructed mass distribution after requiring kinematic cuts to enhance $K^\pm \to \pi^\pm\pi^0$ events and no deposited energy in veto detectors. The Monte Carlo (MC) samples of $K^\pm$ decays are normalized to data based on the $K^\pm$ yield in the signal region. On the other hand, the K_L decay samples were normalized to data with loose selection criteria enhancing the $K_L \to \pi^+\pi^-\pi^0$ decay. We used the events in the signal region to evaluate the inefficiency of UCV. Figure 5 shows the distribution of deposited energy in UCV. We defined the inefficiency as a ratio of the number of events below the energy threshold to the total number of events. Subtracting contamination by K_L decays in the control sample and an effect of accidental hits, we estimated the inefficiency to be $8.0^{+1.1}_{-3.0}\%$ (preliminary).

The $K^\pm$ background in the $K_L \to \pi^0\nu\bar{\nu}$ search was evaluated with a cut using UCV. For the physics data collected in 2021, we estimated the number of $K^\pm$ background events to be $0.043^{+0.016}_{-0.022}$ (preliminary) at the single event sensitivity (SES) of 7.9×10^{-10} (preliminary).

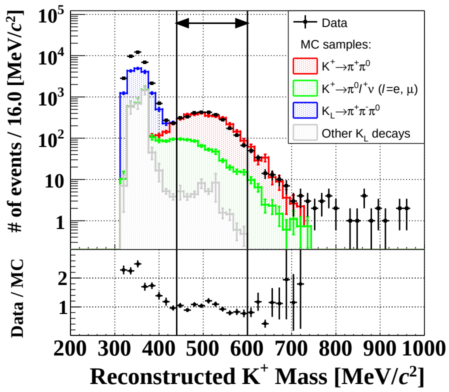

Figure 4. Distribution of the reconstructed invariant mass. The black dots and the colored histograms show data and the MC samples respectively. The area between the two vertical lines corresponds to the signal region.

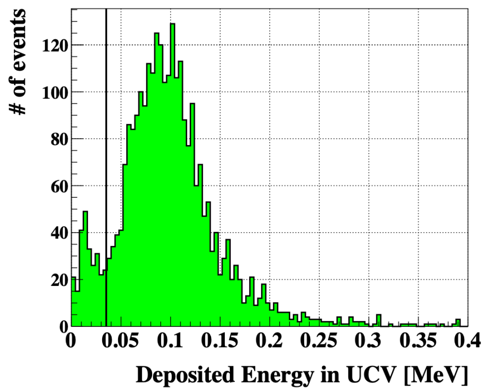

Figure 5. Distribution of the energy deposition in UCV. The black line shows the threshold for veto.

5. Future plans to supress $K^\pm$ background

With the present reduction capability against the $K^\pm$ background, the expected number of $K^\pm$ background events will be still comparable to the number of $K_L \to \pi^0\nu\bar{\nu}$ events at the SM sensitivity of 3×10^{-11}. We thus need to further suppress the $K^\pm$ background in the future. We are currently developing a new charged particle detector [3, 4]. This "new UCV" is expected to have an inefficiency of 1% or less. We plan to replace the current UCV with the new one in 2022.

Another plan is to install an additional magnet at the downstream end of the beam line in 2023. By sweeping away $K^\pm$ from the beam with the magnet, we aim to reduce the flux of $K^\pm$

by a factor of 10 in the future runs. Using the new UCV together with the magnet, we expect to have $\mathcal{O}(10^{-3})$ reduction capability against $K^{\pm}$ background.

6. Conclusions

We developed a charged particle detector, UCV, to reduce $K^{\pm}$ background. By using the control sample of $K^{\pm}$ events, we estimated the inefficiency of UCV to be $8.0^{+1.1}_{-3.0}\%$ (preliminary). With the SES of 7.9×10^{-10} (preliminary), the number of $K^{\pm}$ background events in the $K_L \to \pi^0 \nu\bar{\nu}$ search was suppressed to be $0.043^{+0.016}_{-0.022}$ (preliminary) after applying the veto on UCV.

Acknowledgments

This work was supported by the Japan Society for the Promotion of Science KAKENHI Grants No. JP16H06343, No. JP16H02184, No. JP20K14488, No. JP20K03988 and No. JP21H04995.

References

[1] Buras A J, Buttazzo D, Girrbach-Noe J and Knegjens R 2015 *J. High Energy Phys.* JHEP11(2015)033
[2] Ahn J K *et al.* (KOTO Collaboration) 2021 *Phys. Rev. Lett.* **126**(12) 121801
[3] Ono K 2022 *Proc. Int. Conf. on Kaon Physics 2022* (Osaka)
[4] Kitagawa A 2022 *Proc. Int. Conf. on Kaon Physics 2022* (Osaka)