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Status of the $K_L^0 \to \pi^0\nu\bar{\nu}$ Search at the KOTO Experiment

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KOTO is searching for New Physics through the $K_L^0 \to \pi^0\nu\bar{\nu}$ decay. We report the two major backgrounds of $K_L^0 \to \pi^0\nu\bar{\nu}$ search at KOTO: K_L^0 and K^+ produced at the collimator. In order to suppress them, an in-beam veto counter has been installed at the KOTO detector entrance to detect K^+ particles. Also, an algorithm connecting the cluster shape with the reconstructed incident angle has been developed to suppress the beam halo K_L^0 decays. With those tools, KOTO is prepared to explore the sensitivity of $O(10^{-10})$. We also search for the $K_L^0 \to \pi^0 X$ decay, where X is a hypothetical invisible particle, and set $BR(K_L^0 \to \pi^0 X, M_X \approx M_{\pi^0}) < 3.7 \times 10^{-9}$ (90% C.L.) (preliminary).

7th Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE 2020-2021)
29th November - 3rd December 2021
Bergen, Norway

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PoS(DISCRETE2020-2021)069

1. Introduction

The CP-violating decay $K_L^0 \to \pi^0\nu\bar{\nu}$ has been highlighted as a golden channel to New Physics (NP) beyond Standard Model (SM). Its branching ratio is predicted to be $(3.0 \pm 0.3) \times 10^{-11}$ in SM [1]. If a deviation is observed, it potentially hints NP. Remarkably, based on the weak isospin rotation, $BR(K_L^0 \to \pi^0\nu\bar{\nu})$ has a model-independent constraint of $< 4.3 \times BR(K^+ \to \pi^+\nu\bar{\nu})$ [2]. According to the latest NA62 result [3], the upper limit is $< 6.3 \times 10^{-10}$ (68% C.L.). However, this constraint is circumvented in the interpretation of the hypothetical $K_L^0 \to \pi^0 X$ decay (X is invisible) if X has a mass close to the π^0, because this region is experimentally excluded from the search to suppress the $K^+ \to \pi^0\pi^+$ background [4]. Instead, another upper limit of $< 1.9 \times 10^{-8}$ (90% C.L.) is set for the π^0 mass region [5].

Figure 1 shows the experimental layout of KOTO to search for the $K_L^0 \to \pi^0\nu\bar{\nu}$ decay. A proton beam first strikes a gold target and part of the resulting K_L^0 particles enter the beamline at an angle of 16°. A photon absorber and a magnet are installed to suppress photons and charged particles. Two collimators are implemented to ensure that the K_L^0 beam is narrow. The $K_L^0 \to \pi^0\nu\bar{\nu}$ signal is required to have two photon hits in the calorimeter that consists of 2716 cuboid CsI crystals. By assuming that they are induced by a π^0 decay on the z-axis, the vertex and momentum can be reconstructed. Because of the undetected neutrinos, the π^0 transverse momentum (P_T) is required to be large. The rest of the detector is comprised of veto counters enclosing the entire decay region. Any event that has on-time hits in those components is regarded as a background event.

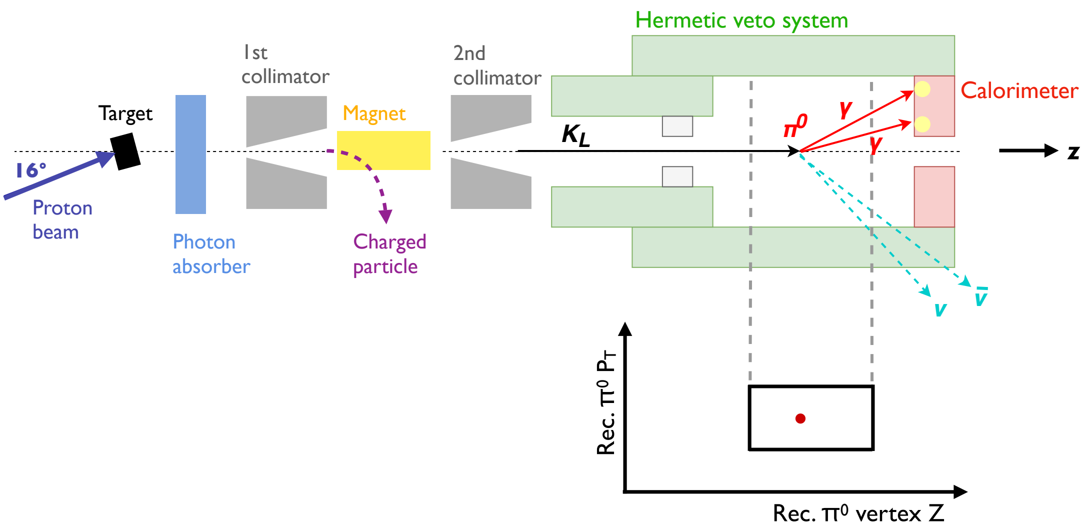

Figure 1: Schematic diagram of the $K_L^0 \to \pi^0\nu\bar{\nu}$ search at KOTO. By convention, the z-axis lies along the beam and points downstream.

2. Summary of the Latest $K_L^0 \to \pi^0\nu\bar{\nu}$ Result

KOTO has published the latest $K_L^0 \to \pi^0\nu\bar{\nu}$ result based on the data collected from 2016 through 2018 [6]. KOTO has reached the single event sensitivity of $(7.20 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$. Although three signal candidate events were found, the signal strength is not statistically significant due to an expected rate of the (1.22 ± 0.26) background events. By applying Poisson statistics, $BR(K_L^0 \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ (90% C.L.) is concluded.

The largest background source is K^+ particles produced at the second collimator. Without magnet's protection, those K^+ particles can enter the KOTO detector. Among K^+ decay modes, the $K^+ \to \pi^0 e^+ \nu$ decay is the dominating source because of the large veto inefficiency against backward e^+ hits, as shown in Figure 2 (a). By measuring the $K^+ \to \pi^0 \pi^+$ decay in 2021, the K^+ to K_L^0 flux ratio is estimated to be $(2.6 \pm 0.1) \times 10^{-5}$, which leads to an estimated number of K^+ background events to be (0.87 ± 0.25).

The second largest background source is beam halo K_L^0 particles, which are scattered at the collimator and enter the detector at a large angle. If a halo K_L^0 decays to two photons near the calorimeter, the reconstructed vertex z is shifted upstream due to the π^0 mass assumption. Because the decay is displaced from the z-axis, it is misinterpreted as missing P_T, as shown in Figure 2 (b). We estimate the halo K_L^0 flux through the $K_L^0 \to 3\pi^0$ decay and obtain (0.26 ± 0.07) halo $K_L^0 \to 2\gamma$ background events.

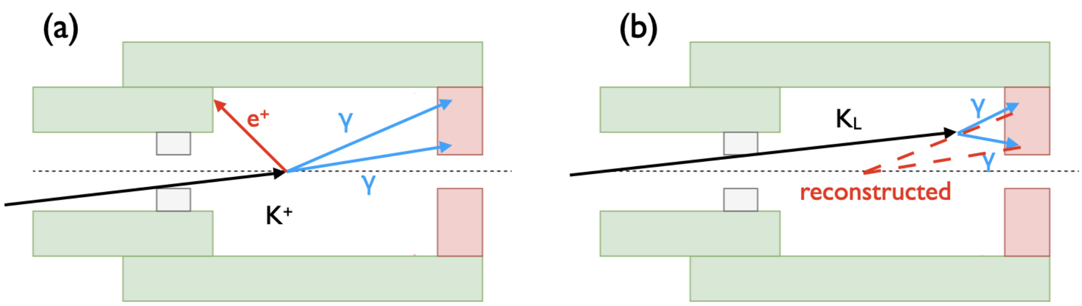

Figure 2: Background mechanism of (a) $K^+ \to \pi^0 e^+ \nu$ decay and (b) collimator-scattered $K_L^0 \to 2\gamma$.

3. Future Prospect

The K^+ background suppression is essential to improve the signal sensitivity. In 2020, the Upstream Charged Veto (UCV) counter shown in Figure 3, which is made of plastic scintillator fibers, was installed at the upstream end of the KOTO detector to detect K^+. According to the electron beam test, an inefficiency of 5% against charged particles is achieved, and the expected number of K^+ decay background events is reduced to 1 at the SM sensitivity.

The suppression of the second largest background source, halo $K_L^0 \to 2\gamma$ decay, relies on the algorithm illustrated in Figure 4. Various probability density functions (PDF) are initially established to evaluate the likelihood of a reconstructed incident angle developing into a given cluster shape. The likelihood is calculated for the following two scenarios: One is that $\pi^0 \to 2\gamma$ decays on the beam axis and the other is that $K_L^0 \to 2\gamma$ decays at the COE (center of energy) axis (parallel to the beam axis but points to COE). A likelihood ratio (LR) is then obtained. A background reduction efficiency of 85% can be achieved at 90% signal efficiency.

Figure 5 shows the accumulated number of protons on target (POT) versus the time. The number of K_L^0 decays collected from 2019 through 2021 is approximately doubled of that from

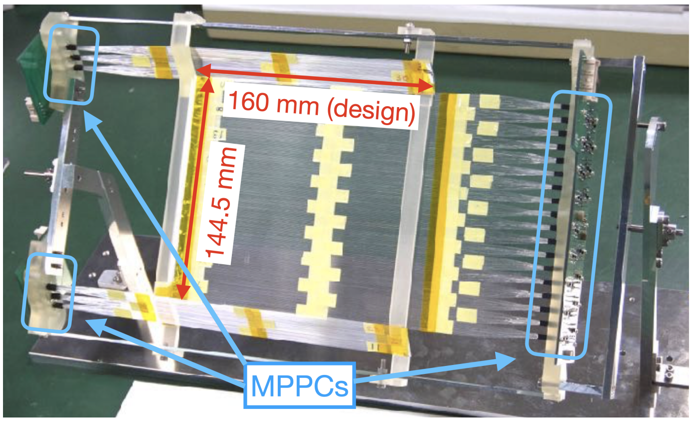

Figure 3: Photograph of UCV. Scintillation lights are transmitted through 0.5-mm square fibers and collected by Multi-Pixel Photon Counters (MPPC).

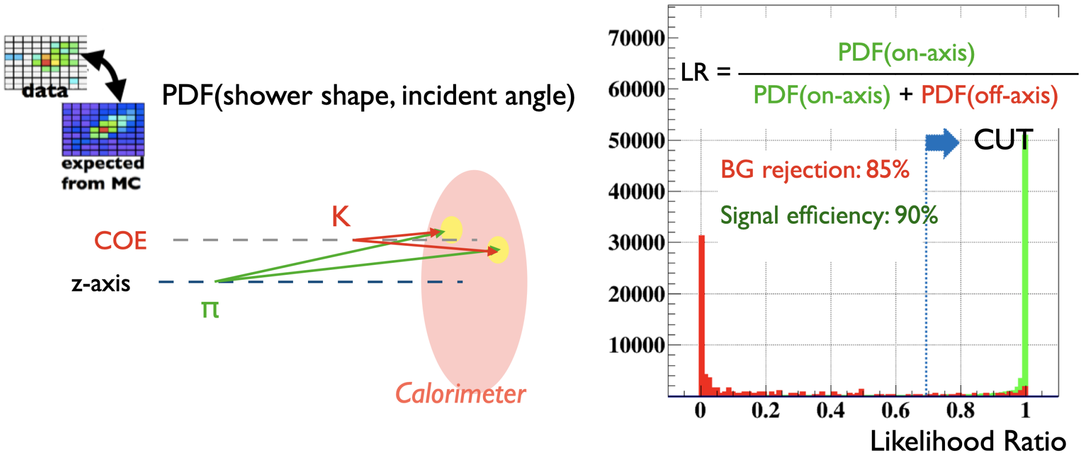

Figure 4: Algorithm of the halo $K_L^0 \to 2\gamma$ discrimination and its performance.

2016 through 2018. However, because UCV is absent in the data collected in 2019 and 2020, an artificial neural network (ANN) method with kinematic variable inputs is proposed to maximize the suppression power against the K^+ decay background. The data collected in 2021 is critical to examine the UCV performance. In the future, the beam intensity will be gradually upgraded to 100 kW. With less background contamination, KOTO is prepared to explore the sensitivity of $O(10^{-10})$.

4. Hypothetical particle X Interpretation

To search for the $K_L^0 \to \pi^0 X$ decay, we used the same signal region and data set. Thus, the estimated number of background events and the number of K_L^0 decays are identical with those for the $K_L^0 \to \pi^0 \nu\bar{\nu}$ search. The only difference is that the signal acceptance is evaluated for the $K_L^0 \to \pi^0 X$. We assumed that the X particle is feebly interacting and scanned a mass in the range of 0 – 280 MeV, as instanced in Figure 6. Besides the stable particle assumption, $X \to e^+e^-$ with a finite lifetime in the range of 0.1 – 5 ns is also considered.

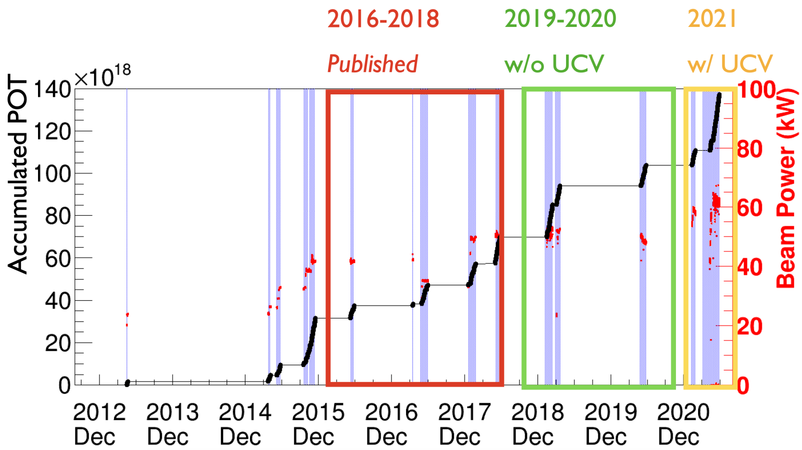

Figure 5: Accumulated Protons On Target (POT) and the associated beam intensity since 2013.

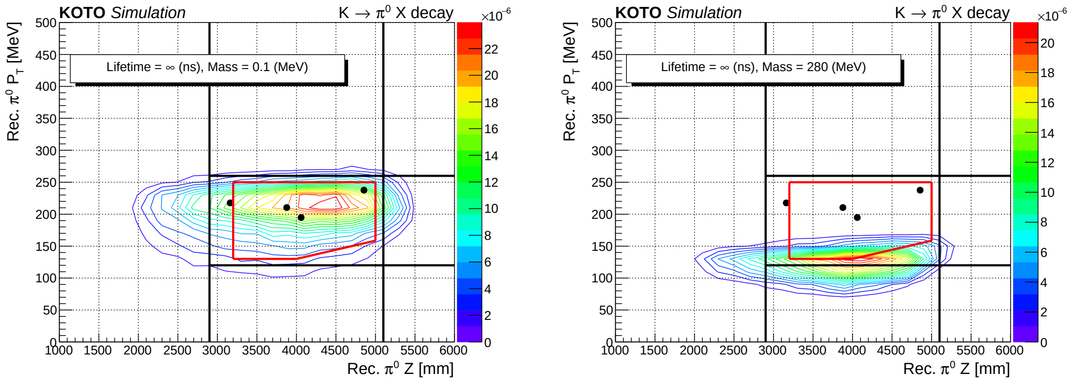

Figure 6: $K_L^0 \to \pi^0 X$ signal contours for stable X particle with mass of 0.1 MeV (left) and 280 MeV (right). z-axis represents the likelihood of where to find expected signal events. The red frame represents the final signal region and the four black dots are the remaining events of the real data in the central box.

Figure 7 shows the upper limit of $Br(K_L^0 \to \pi^0 X)$ by assuming the Poisson statistics. Heavy X particles tend to have smaller acceptance due to limited P_T. The shorter the lifetime is, the more likely the resulting $e^\pm$ particles are detected for veto. The light particles have smaller dependence on lifetime because they are more boosted.

5. Conclusion

The data collected from 2016 through 2018 reveals that K_L^0 and K^+ produced at the collimator are the two major background sources. By introducing the charged veto counter and cluster shape analysis, both background sources can be controlled to the SM sensitivity. An interpretation of the hypothetical $K_L^0 \to \pi^0 X$ decay suggests that the branching ratio of $K_L^0 \to \pi^0 X$, where X is steady and has mass of π^0, is estimated to be $< 3.7 \times 10^{-9}$ (90% C.L.) (preliminary).

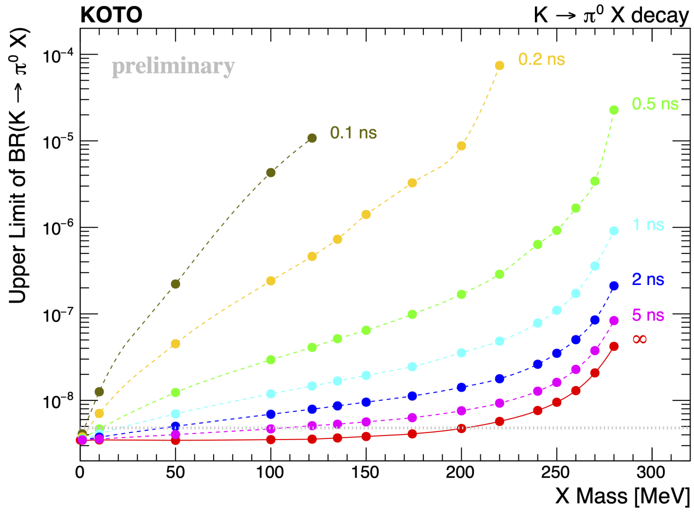

Figure 7: $K_L^0 \to \pi^0 X$ branching ratio of various X mass and lifetime. The gray dashed line indicates the result from the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay analysis.

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