Status and Prospect of KOTO-I

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Abstract. KOTO is the first experiment with the designed sensitivity of O(10^{-11}) to probe for new physics through the rare \( K^0_L \to \pi^0 \nu \bar{\nu} \) decay. From 2017 to 2019, there were critical changes in the data acquisition system that further improved the research potential of KOTO for diverse research topics. In this article, we present the new trigger system of KOTO and several byproduct analysis.

1. Introduction
We present the potential of studying other physics topics than \( K^0_L \to \pi^0 \nu \bar{\nu} \) in KOTO-I, thanks to an upgraded data acquisition system (DAQ). This new DAQ not only resolved the trigger issue (discussed in Sec. 2) in KOTO-I but also enabled KOTO to perform various physics studies. We are particularly interested in measuring the \( K^0_L \to \pi^0 e^+ e^- \) decay in KOTO because it shares the same CP-violating component with the \( K^0_L \to \pi^0 \nu \bar{\nu} \) decay.

2. New Trigger system
The KOTO experiment has a unique design of hermetic veto system, and it utilizes one of the world’s highest proton beam intensity accelerators, J-PARC. These make KOTO the best place to study rare neutral kaon decays. However, initially, the analysis capability of KOTO was limited by the trigger system. We only had a trigger based on the center of energy of the clusters in the CsI calorimeter [1]. This trigger collected the \( K^0_L \to \pi^0 \nu \bar{\nu} \) data with the signature of high transverse momentum (\( p_T \)), but it discarded other research possibilities of low \( p_T \) decay channels, such as the \( K^0_L \to \pi^0 \gamma \gamma \) and \( K^0_L \to \pi^0 e^+ e^- \) decays.

The new trigger system [2] used two types of custom-made electronics modules shown in Fig. 1, designed by the University of Chicago. There are two levels of triggers. The first level was determined by requiring a certain amount of energy deposited in the CsI calorimeter and no energy in the rest of the detectors. The second-level trigger counts the number of clusters in the CsI calorimeter, which enabled KOTO to collect variant decay modes efficiently, such as the \( K^0_L \to \pi^0 \gamma \gamma \) and \( K^0_L \to \pi^0 e^+ e^- \) decays.

The trigger system was upgraded in three incremental steps. First, we replaced the second-level trigger with the cluster-counting system in 2017, and the DAQ live ratio was recovered from an average of 80% back to 97%, as shown in Fig. 2. The collection of \( K^0_L \to \pi^0 \gamma \gamma \) and \( K^0_L \to \pi^0 \pi^0 \nu \bar{\nu} \) data has started since then. Later, we implemented the new first-level trigger system to cope with the beam power increase in 2018, which preserved the high DAQ live ratio.
Figure 1. New trigger processors: Clock Distribution and Trigger (CDT) processor (left), and Optical Fiber Center (OFC) module (right).

at 97% while the beam power increased by 20% to 50 kW. Finally, to improve the overall system stability, we replaced a sub-system for trigger calculation in a custom-made VME backplane [1] with full optical fiber techniques using the new CDT and OFC modules [2]. This final upgrade in 2019 pushed the DAQ live ratio to 99%, and it is expected to preserve such high efficiency even with a factor of two increase in the beam power up to 100 kW.

Figure 2. DAQ live ratio and the beam power in each period of data-taking.
3. Analysis

3.1. Analysis of $K_L^0 \rightarrow \pi^0 e^+ e^-$

We are particularly interested in measuring the $K_L^0 \rightarrow \pi^0 e^+ e^-$ decay in KOTO because this decay has excellent sensitivity to new physics as it shares the same direct CP-violating process with the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ decay, as shown in Fig. 3. Although there are also indirect CP-violating and CP-conserving components in the $K_L^0 \rightarrow \pi^0 e^+ e^-$ decay, those can be extracted by other experimental measurements from $K_S^0 \rightarrow \pi^0 e^+ e^-$ and $K_L^0 \rightarrow \pi^0 \gamma \gamma$ searches. In a possible scenario of new physics discovery in $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$, the result of $K_L^0 \rightarrow \pi^0 e^+ e^-$ is a critical piece of supporting evidence.

Figure 3. Feynman diagrams of the $K_L^0 \rightarrow \pi^0 e^+ e^-$ decays: (a) Direct CP-violating, (b) Indirect CP-violating, and (c) CP-conserving components.

One of the essential requirements to perform the $K_L^0 \rightarrow \pi^0 e^+ e^-$ search in KOTO is the particle discrimination between $\pi^\pm$ and $e^\pm$ in order to suppress the $K_L^0 \rightarrow \pi^0 \pi^+ \pi^-$ background events. By using the $K_L^0 \rightarrow \pi^0 \pi^+ \pi^-$ data taken in 2019, we developed an algorithm involving machine learning based on the cluster shape and pulse shape measured in the CsI calorimeter. The results showed that the $K_L^0 \rightarrow \pi^0 \pi^+ \pi^-$ background could be suppressed by six orders of magnitude using the $\pi^\pm/e^\pm$ discrimination, and another five orders of magnitude with requirements on kinematic variables. Therefore, the $K_L^0 \rightarrow \pi^0 \pi^+ \pi^-$ background is negligible. Other possible background sources from $K_L^0 \rightarrow \pi^0 \pi^0$ and $K_L^0 \rightarrow \gamma \gamma e^+ e^-$ were studied based on the MC simulation, and the preliminary results predict one $K_L^0 \rightarrow \gamma \gamma e^+ e^-$ background event at the signal sensitivity of $8 \times 10^{-11}$ at KOTO-I.

However, one of the challenges in the $K_L^0 \rightarrow \pi^0 e^+ e^-$ study is in the DAQ. When including $K_L^0 \rightarrow \pi^0 e^+ e^-$ in the trigger, the rate is expected to increase by a factor of two. The rise of the trigger rate is mainly due to mis-reconstructed $K_L^0 \rightarrow \pi^0 \pi^+ \pi^-$ events passing the $K_L^0 \rightarrow \pi^0 e^+ e^-$ requirements, and the bottleneck in DAQ is the data throughput to the Level-III
PC farm system. Therefore, we are now working on the upgrade of Level-III, and we expect to start collecting $K^0_L \rightarrow \pi^0 e^+ e^-$ data after 2020.

3.2. Analysis of $K^0_L \rightarrow \pi^0 \pi^0 \nu \bar{\nu}$
The flavour changing neutral current $K^0_L \rightarrow \pi^0 \pi^0 \nu \bar{\nu}$ decay is a CP conserving process and its branching ratio is sensitive to the real part of the $s \rightarrow d \nu \bar{\nu}$ transition amplitude. The current best upper limit on the branching ratio is $8.1 \times 10^{-7}$ set by the E391a experiment [3]. Since 2017, KOTO has collected about 20 times more data than E391, and we expect to update the results of this measurement shortly.

3.3. Analysis of $K^0_L \rightarrow \pi^0 \gamma \gamma$
The $K^0_L \rightarrow \pi^0 \gamma \gamma$ measurement is critical for extracting the $\alpha_V$ parameter in the Chiral perturbation theory and estimating the CP-conserving component in the $K^0_L \rightarrow \pi^0 e^+ e^-$ decay. So far, there are two measurements from the NA48 [4] and the KTeV [5] experiments, where two results barely agree, shown in Fig. 4. KOTO experiment will perform the third measurement shortly.

![Figure 4](image_url)

**Figure 4.** Historical measurements of $\alpha_V$ from the NA48 and KTeV experiments.

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