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First Search for $K_L^0 \to \pi^0 e^+ e^- e^+ e^-$ Decay Mode

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The first search for $K_L^0 \to \pi^0 e^+ e^- e^+ e^-$ is performed with a dataset collected by the J-PARC KOTO experiment in 2021. In the dark sector model, this final state can be achieved through $K_L^0 \to \pi^0 XX$, where $X \to e^+ e^-$ [1]. The branching ratio of this decay mode is predicted to be $O(10^{-10})$ dominated by the virtual photon vertex through $K_L^0 \to \pi^0 \gamma^* \gamma^*$ in the Standard Model. With the data collected in 2021, we can achieve a sensitivity close to this level which can improve the constraints on the dark sector model. Special analysis methods are used for the rejection of backgrounds related to the π^0 Dalitz decay. The result of the analysis based on data taken in 2021 will be discussed.

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1. Introduction

KOTO is an experiment primarily searching for the ultra rare decay $K_L \to \pi^0 \nu\bar{\nu}$ [2]. This search requires a high intensity of K_L beam and high precision of trigger and data acquisition system which sets KOTO a unique position to search for rare Kaon decay mode with multiple charged leptons in its final state. One of these modes is $K_L^0 \to \pi^0 e^+e^-e^+e^-$ which has never been experimentally measured before.

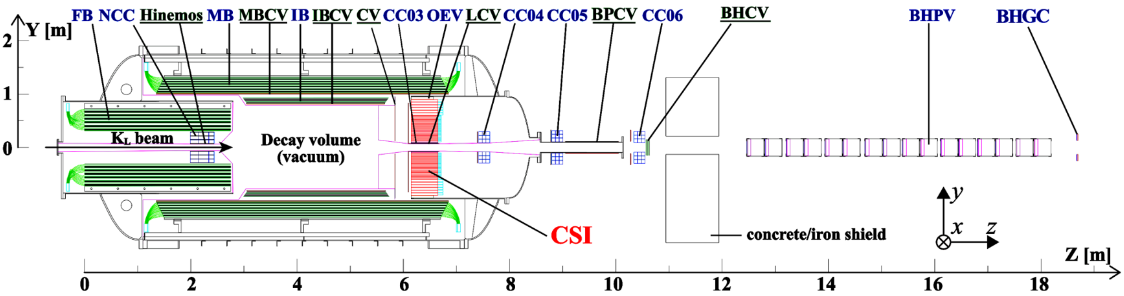


Figure 1: A cross-sectional side view of the KOTO detector with the beam entering from the left. Direction of beam is denoted as Z axis. The main CsI calorimeter is denoted in red, while names of charged particle counter in green with an underline and photon veto counters in blue.

This decay mode is particularly interesting for its potential as a probe to light dark particle X. The final state $\pi^0 e^+e^-e^+e^-$ can be achieved through $K_L^0 \to \pi^0(XX \to 2(e^+e^-))$ which may have very large rate, exceeding the Standard Model expectation [1]. One recently proposed model of an MeV-scale QCD axion suggests that the direct nonlinear interaction between axion with the light meson, π^0 in this case, can give rise to large rates for this kind of kaon decays with multilepton signatures. They propose that an experimental search with a precision at the level of $O(10^{-6})$ and better can set new limits on their dark sector model.

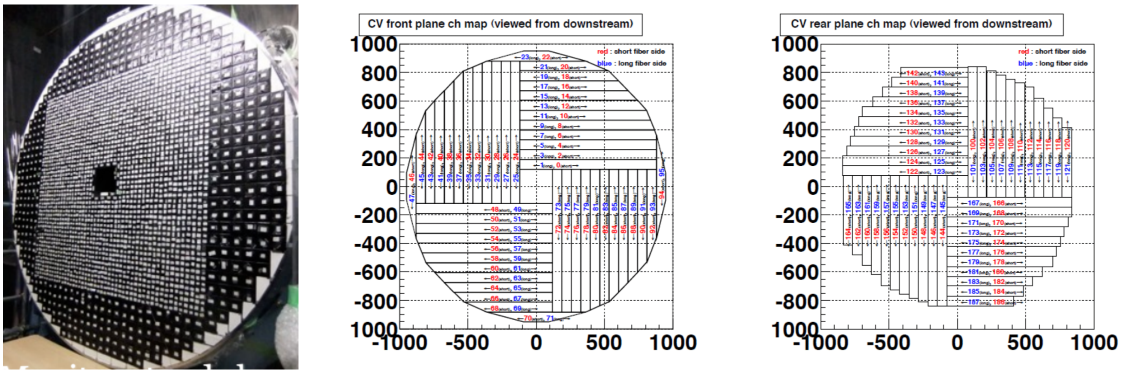
Although the theoretical prediction of this decay mode within SM is missing, it is highly likely to be dominated by the virtual photon counter part of $K_L^0 \to \pi^0\gamma\gamma$ with 2 γ internally convert to e^+e^-, similar to its charged counter part $K^+ \to \pi^+e^+e^-e^+e^-$ which is calculated theoretically within SM [3]. Based on the measured branching ratio $\mathcal{BR}(K_L^0 \to \pi^0\gamma\gamma) \approx 1.2 \cdot 10^{-6}$, the corresponding decay $K_L^0 \to \pi^0(\gamma^*\gamma^* \to 2(e^+e^-))$ is likely at the order of $O(10^{-10})$ making this decay a perfect test bench for new physics [1,4].

2. Experimental Methods

2.1 Apparatus

In the decay $K_L^0 \to \pi^0 e^+e^-e^+e^-$, there are six final state particles: two photons and two pairs of electron and positron. All of them will be observed as electromagnetic shower cluster in our CsI (Cesium Iodide) calorimeter. Our CsI is composed of 2716 undoped Cesium iodide crystals as shown in Fig.2a, which can precisely measure the time, poistion, and energy deposited of a hit.

Another subdetector that plays a vital role in this search is CV (Charged Veto) detector which is placed upstream of CsI as shown in Fig.1. CV is a charged particle counter used as a Veto detector in our primary search for $K_L \to \pi^0 \nu\bar{\nu}$. In the special runs used in this search, CV is not used as a Veto trigger but the opposite. For data-taking runs with this special trigger condition, only an event with at least 1 hit on CV is kept, enabling us to get rid of the huge contribution from the most relevant backgrounds like $K_L^0 \to 3\pi^0$ at the trigger level.



(a) A view of CsI calorimeter **(b)** Schematic Diagram showing module map of CV

Figure 2: Picture and figures of the two most relevant KOTO detectors in this study

CV consists of two layers of scintillation counter planes which have modules in strip as shown in Fig.2b. Due to this structure, the charged particle hit position can not be directly determined on transverse plane. Our charged particle identification relies on the mapping between expected hit position from reconstruction and the location of CV modules with energy deposited.

2.2 Blind Analysis

The signal signature of $K_L^0 \to \pi^0 e^+ e^- e^+ e^-$ is 2 photons and 4 electron/positron on target. Since every final particle will be measured directly by our main CsI calorimeter, the resultant reconstructed K_L^0 mass should correctly reflect the true K_L^0 invariant mass. Since kaons enter decay region along the beam axis and there is no missing resultant particle, the reconstructed K_L^0 transverse momentum should be close to zero.

To minimize any potential source of bias, we performed blind analysis strategy for this rare decay search. A blind region is defined on the reconstructed K_L^0 mass (Rec M_{K_L}) and reconstructed K_L^0 transverse momentum (Rec P_T) plane as 440 MeV < Rec M_{K_L} < 540 MeV and 0 MeV^2 < Rec P_T^2 < 200 MeV^2.

3. Analysis

3.1 Reconstruction

Signal event reconstruction relies on kinematics and the charged particle identification with the aid of CV detector. Based on Monte Carlo events generated with Geant4 on KEKCC (KEK central computer system), the reconstruction algorithm developed for this signal decay follows these steps:

1. Selecting events with 6 clusters identified on CsI.

2. Finding the decay vertex Z position via Eq.1, while assuming the K_L^0 mass. The K_L^0 x, and y decay position is assumed to be equal to the COE (Center of Energy) on the CSI. θ_{ij} represents the opening angle between the trajectories of ith and jth final particles.

$$M_{K_L^0}^2 = \sum_{i<j}^{6} 2E_i E_j (1 - \cos\theta_{ij}) \tag{1}$$

3. Using K_L^0 Vertex to determine the hit position of all 6 final particles on CV.
4. Mapping the 6 hit positions on CV with CV measurements and identify any charged particle out of the 6 final particles.
5. Keeping events with 4 charged particles and 2 uncharged particles. Using the two uncharged particle (supposedly 2γ from the same π^0) to reconstruct π^0 vertex based on Eq.2 assuming π^0 mass.

$$M_{\pi^0}^2 = 2E_{\gamma_1} E_{\gamma_2} (1 - \cos\theta_{12}) \tag{2}$$

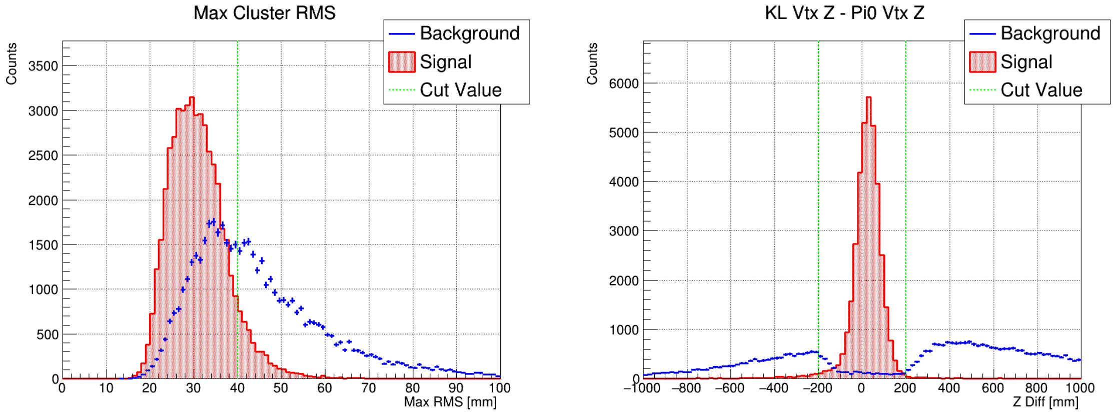
3.2 Background Decays

With the above reconstruction, there are still contributions from several background decays for their high branching ratio and different mechanism. Five major backgrounds are considered with large amount of Monte Carlo data generated with KEKCC and OSG (Open Science Grid). Other backgrounds that are proved to be negligible from preliminary study, including K^+ decays and $K_L^0 \to \pi^0\pi^0$, are not listed in Table.1.

Decay Nickname	Decay Mode	$\mathcal{BR}$	N_{exp}	N_{MC}
π+ - 0	$K_L^0 \to \pi^+\pi^-\pi^0$	0.1254	$1.84 \cdot 10^{11}$	$6.03 \cdot 10^{11}$
3 π^0	$K_L^0 \to \pi^0\pi^0\pi^0$	0.1952	$2.87 \cdot 10^{11}$	$3 \cdot 10^{12}$
3 π^0 1 Dalitz	$K_L^0 \to \pi_D^0\pi^0\pi^0$	$2.2 \cdot 10^{-3}$	$3.2 \cdot 10^{9}$	$1.1 \cdot 10^{10}$
3 π^0 2 Dalitz	$K_L^0 \to \pi_D^0\pi_D^0\pi^0$	$2.6 \cdot 10^{-5}$	$3.8 \cdot 10^{7}$	$8.4 \cdot 10^{9}$
3 π^0 double Dalitz	$K_L^0 \to \pi_{DD}^0\pi^0\pi^0$	$6.3 \cdot 10^{-6}$	$9.3 \cdot 10^{6}$	$2.4 \cdot 10^{9}$

Table 1: List of major contribution of background decays. N_{exp} represent the approximate expected number of events in data, calculated based on branching ratio ($\mathcal{BR}$) and total number of K_L^0. $\mathcal{BR}$ listed here is according to PDG or with simple extrapolation [4]. N_{MC} represent the number of Monte Carlo events simulated. π_D^0 denotes that π^0 with Dalitz decay ($\pi^0 \to \gamma e^+ e^-$).

For the leftover events of these five backgrounds, the key features are mainly non-leptonic charged particle hits on CV and fusion of clusters on CsI. The first is the main source of $\pi + -0$ which has two charged particles π^+ and π^-. This source can be effectively suppressed by a series of cluster shower shape cut since the hadronic shower shapes are significantly different from the signal. Similarly, background from fusion of clusters which means two adjacent clusters are considered as one cluster by the algorithm can also be reduced by shape cut. One example of shape cut is provided in Fig.3a. A neural network model called Cluster Shape Discrimination (CSD) was also implemented to further reduce the contribution from $\pi + -0$ [5]. Missing particle or misidentification of charged particle are also relevant. In such cases, some kinematic variables will reflect the missing energy or wrong reconstruction as the example cut shown in Fig.3b.



(a) Cluster root-mean-square is a measure of cluster size, see definition in p122 of [6]. Events with maximum RMS above 40mm are removed.

(b) The difference between reconstructed K_L^0 vertex z and reconstructed π^0 vertex z should be close to 0 for signal events. Events with ΔZ outside [-200mm, 200mm] are removed.

Figure 3: Examples of physics cuts developed for background reduction

With the complete set of cuts, the background level of all above mentioned five decays is reduced to zero outside blind region. And the expected number of background events inside signal region is $0.05 \pm 0.02 \pm 0.01$ with contribution from $K_L^0 \to \pi_D^0 \pi_D^0 \pi^0$ and $K_L^0 \to \pi_{DD}^0 \pi^0 \pi^0$. If we include the 90% C.L. upper limit from the other three sources, we expect number of observed background to be $< 1.63 \pm 0.02 \pm 0.01$.

With this cut set, the Single Event Sensitivity (SES) for $K_L^0 \to \pi^0 e^+e^-e^+e^-$ is calculated with K_L^0 yield (Y) obtained from normalization to $3\pi^0$ with a different trigger,

$$SES = \frac{1}{Y \cdot A_{sig}} \approx 1.79 \times 10^{-7} \tag{3}$$

in which acceptance of signal events (A_{sig}) is obtained from Monte Carlo simulation of signal events assuming $K_L^0 \to \pi^0 XX, (X \to e^+e^-)$ where light dark particle X has a rest mass of 100 MeV.

4. Results

After finalizing the analysis, the blind region, as shown by the bottom central box in Fig.4, was opened and 0 events were observed. This result is consistent with background estimation. Assuming Poisson statistics with a SES of 1.79×10^{-7}, we set an upper limit on the branching ratio of this decay $K_L^0 \to \pi^0 e^+e^-e^+e^-$ to be $< 4.11 \times 10^{-7}$ at the 90% C.L.

5. Summary and Future Prospects

We performed the first experimental search of K_L^0 decay to $\pi^0 e^+e^-e^+e^-$ final state in KOTO experiment. We observed no signal event after opening box. A first upper limit of branching ratio of

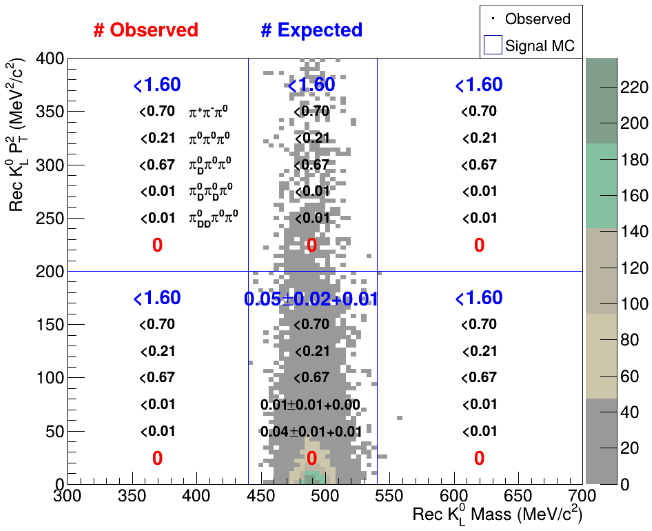


Figure 4: Event distribution of physics data, background MC, and signal MC on RecM_{K_L}-RecP_T^2 plane after opening box. The red numbers represent the number of observed events in physics data. The blue numbers represent the total number of observed events (or the 90% C.L. upper limit) in background MC. The black numbers are the breakdown of blue number for each source. And the colored distribution is the event display of signal MC. Note that all the sideband regions include regions outside the boundary of this plot.

$K_L^0 \to \pi^0 e^+ e^- e^+ e^-$ via $K_L^0 \to \pi^0 XX$, $(X \to e^+ e^-)$ with $M_X = 100$MeV is set to be $< 4.11 \times 10^{-7}$ at the 90% C.L. More constraints can be set to this light dark particle model by simulating this signal decay channel with different X mass. The next step of completing our analysis is producing a set of upper limit for different X mass within the possible range of $2M_e < M_X < (M_{K_L^0} - M_{\pi^0})/2$.

To further advance on searching for $K_L^0 \to \pi^0 e^+ e^- e^+ e^-$, the improvement on signal sensitivity is necessary. More investigation to CV detector response can be useful to improve signal acceptance. Since the current background level is low, collecting more data would be effective to further improve the upper limit. In case of new data taking, a special treatment to online trigger for CV could be applied to better suppress backgrounds with less than four charged particles or non-leptonic charged particle.

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