Dark Sector studies with KOTO

KOTO Collaboration

In recent years, the Dark world has been explored in high energy physics by several experiments, and enormous efforts have been made on searching a new type of massive gauge boson, the dark photon (A')[1]. Theoretically, the dark photon could interact with ordinary particles through direct kinetic mixing with the electromagnetic photon. Conventionally, the experimental results were parametrized into the coupling strength of the dark photon as the function of its mass. However, this parameter space has been tightly constrained with only a little room left, and no sign of existence has been observed so far. This turned our interest towards searching another type of dark photon, the massless dark photon ($\bar{\gamma}$). Unlike the massive one, the massless dark photon has no direct mixing with the ordinary photon, but it could interact with the SM particles through effective coupling to the quarks, and the coupling strength is waiting to be measured. We outlined the possibilities of exploring the massless dark photon at the KOTO experiment[2][3].

The primary goal of KOTO is to probe the ultra-rare $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay. To cope with the missing energy taken by neutrinos, KOTO adopted a design concept of the hermetic system with a series of detectors enclosing the decay volume of kaon. The detector's main component is the CsI calorimeter (CsI) to measure the energy and position of photons. The other detector components surrounding the decay volume, or in/along the beampipe, are used as "veto" to capture missing particles escaped from CsI. Since the momentum of incoming kaons peaks at only 1.4 GeV/c, the detectors and the back-end electronics were built to be sensitive to the energy range of sub-MeV to several GeV. This brought KOTO to an excellent position to hunt rare decay processes of the neutral kaon, especially one with missing energy, such as the dark photon searches.

There are some theoretical calculations of the massless dark photon in the kaon decays [4], and here, we discuss some potential searches in KOTO.

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0.1. $K_L^0 \to \gamma\bar{\gamma}$

As predicted by [4], the massless dark photon could appear in the $K_L^0 \to \gamma\bar{\gamma}$ decay with the theoretical branching ratio as high as $\mathcal{O}(10^{-3})$, which is well within the sensetivity of KOTO. The $K_L^0 \to \gamma\bar{\gamma}$ has only one observable particle in the final state so that the event signature is one photon cluster in CsI with no coincident signals in the other detectors. Two possible backgrounds might come in $K_L^0 \to \gamma\bar{\gamma}$: Neutron and the $K_L^0 \to \gamma\gamma$ decay. The neutron background was caused by the beam neutron interactions with CsI, and the interaction produced a photon-like cluster. The neutron background was also one of the significant background sources in the $K_L^0 \to \pi^0\nu\bar{\nu}$ analysis. Since 2015, KOTO has developed several software and hardware tools to control this background. In the software, we developed neutron/gamma discriminations based on the cluster patterns in the CsI and the pulse waveform recorded by the ADC modules. The combined reduction power on a single neutron cluster is around $\mathcal{O}(10^{-3})$. In the hardware, we instrumented the dual-end readout on CsI to measure the shower depth from the timing difference between two ends. The idea was based on that the gamma shower typically happens near the front-end surface of the CsI, while the neutron shower evenly distributes along with the CsI. This shower depth measurement brought us another factor of $\mathcal{O}(10)$ reduction on the neutron. We expect the combined reduction power on the neutron cluster to be good enough for the $K_L^0 \to \gamma\bar{\gamma}$ search. The suppression of the $K_L^0 \to \gamma\gamma$ background mainly relied on the detection of the escaping photon, pinning the advantage of searching this decay in KOTO, since the KOTO detector entirely covered the fiducial decay volume of kaon. In the summer of 2020, we collected data for this search.

0.2. $K_L^0 \to \pi^0\gamma\bar{\gamma}$

The $K_L^0 \to \pi^0\gamma\bar{\gamma}$ decay, with theoretical branching ratio as high as $\mathcal{O}(10^{-3})$, is also a possible search for the massless dark photon, . The signature of $K_L^0 \to \pi^0\gamma\bar{\gamma}$ decay is three γ's detected in CsI, and a missing momentum from $\bar{\gamma}$. The event is reconstructed by imposing two γ's have an invariant mass of the nominal mass of π^0, and the decay vertex is on the beam axis. Unlike the search for $\pi^0 \to \gamma\bar{\gamma}$ using the $K_L \to 3\pi^0$ decay, the energy of K_L cannot be reconstructed unless the mass of $\bar{\gamma}$ is determined. Moreover, the combination of two γ's to form the π^0 out of three γ's is not uniquely determined. The feature of this decay is, therefore, the large missing transverse momentum from the $\bar{\gamma}$. The dominant background may come from the $K_L \to 2\pi^0$ and $K_L \to \pi^0\gamma\gamma$ decays, where one of γ's is not detected by the detector or two γ's fuse due to the overlap of hits in CsI. These backgrounds can be suppressed by the requirement of large missing transverse momentum.

0.3. $\pi^0 \to \gamma\bar{\gamma}$

The abundant statistics of π^0 from the $K_L \to 3\pi^0$ decay provides an opportunity to search for the $\pi^0 \to \gamma\bar{\gamma}$ decay. The signature of this decay is five γ's in CsI with a missing momentum taken by $\bar{\gamma}$. The decay is reconstructed by requiring the invariant mass of two-gamma pairs to have the nominal mass of the π^0, the decay vertex on the beam axis, and a non-zero transverse momentum of K_L. Without assuming the mass of $\bar{\gamma}$, the energy of K_L can be reconstructed though there are generally two solutions. The invariant mass of the missing four-momentum can be used to measure the mass of $\bar{\gamma}$. In particular, this variable is useful to search for a massive $\bar{\gamma}$ to reduce the backgrounds: the $K_L \to 2\pi^0$ decay associated with an accidental neutron hit on CsI, and the $K_L \to 3\pi^0$ decay in which all the π^0s decay into 2γ and one of γ's is not detected in the detector. To analyze this decay, precise knowledge of the inefficiency of the detector is necessary. In terms of the performance of the inefficiency veto detectors, $\mathcal{B}(\pi^0 \to \gamma\bar{\gamma}) < 10^{-3}$ can be easily achieved, and further constraint of the mass of $\bar{\gamma}$ may improve the sensitivity by a factor of $\mathcal{O}(10)$.

0.4. $K_L \to 2\pi^0\bar{\gamma}$

Similar to the prediction of $K^+ \to \pi^+\pi^0\bar{\gamma}$ by [6], the $K_L \to 2\pi^0\bar{\gamma}$ decay is a potential search for the massless dark photon in KOTO. The upper limit of this decay can be extracted from the $K_L \to 2\pi^0\nu\bar{\nu}$ study, which was performed previously by the E391a experiment at KEK [5]. The obtained upper limits were 10^{-6}-10^{-5} at 90% C.L. for the mass region of $\bar{\gamma}$ from 50 MeV to 200 MeV. The signature of this decay is four γ's and no coincident hits in the veto detectors. The event is reconstructed by imposing the two sets of 2γ's form the invariant masses equal to the nominal mass of π^0, and the decay vertex is on the beam axis. Two-dimension distribution of the magnitude of the missing transverse momentum and invariant mass of two π^0's, is used to examine the $K_L \to 2\pi^0\bar{\gamma}$ decay. In the analysis of E391a, there were no events in the signal region, and thus there is room to improve the sensitivity with much larger statistics of kaon in the KOTO experiment. Given the acceptance of $K_L \to 2\pi^0\bar{\gamma}$ decay is same as $K_L \to 2\pi^0\nu\bar{\nu}$ decays, the single event sensitivity available with one month KOTO data corresponds to $\mathcal{O}(10^{-8})$, which is 30 times larger than E391 analysis. The dominant background contribution may come from the $K_L \to 3\pi^0$ decay, where two γ's are not detected due to the inefficiency of detectors or overlap of γ's hits in CsI.

0.5. $K_L \to \pi^0 a$

Another interesting search is to look for axiflavon (a) [7][8] in the $K_L \to \pi^0 a$ decay. This search goes along with the KOTO primary $K_L^0 \to \pi^0 \nu\bar{\nu}$ study, since both decays share the same event signatures, two photons in CsI and no extra signals in other detectors. The projection sensitivity extracted from the $K_L^0 \to \pi^0 \nu\bar{\nu}$ study is around 10^{-11} at KOTO step-I.

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[6] M. Fabbrichesi *et al.*, Phys. Rev. Lett. 119, 031801 (2017the obtained upper limits were 10^{-6}-10^{-5} at 90% C.L. for the mass region of $\bar{\gamma}$ from 50 MeV to 200 MeV.).

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