Search for the pair production of dark particles in K_L^0 decays at KOTO

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Abstract. We present the first search for the pair production of dark particles X in K_L^0 decays assuming that X decays into two photons promptly. No signal was observed in the mass regions of 40 – 110 MeV/c^2 and 210 – 240 MeV/c^2. This leads to $\mathcal{B}(K_L^0 \to XX) < (1\text{–}4) \times 10^{-7}$ and $\mathcal{B}(K_L^0 \to XX) < (1\text{–}2) \times 10^{-6}$ at the 90% confidence level for the two mass regions, respectively.

1. Introduction

Dark particles (X) may appear in the $s \to d$ quark transition. If dark particles are produced in a pair, the accessible mass regions are different between K_L^0 decays and K^+ decays. The reason is that K^+ mesons need to further couple to an extra charged particle (e.g. π^+) to conserve charge. If X has a mass between $(M_{K_L^0} - M_{\pi^+})/2$ and $M_{K_L^0}/2$, K_L^0 is in a unique position to search for. $K_L^0 \to XX$ can be experimentally studied if X decays into two photons promptly via a heavy quark loop. By using the data collected at KOTO, we present the first search for $K_L^0 \to XX$ with $X \to \gamma\gamma$.

KOTO is a dedicated experiment to measure the ultra-rare decay $K_L^0 \to \pi^0 \nu \overline{\nu}$ [1, 2]. The rareness requires a high intensity K_L^0 beam to reach the sensitivity. The signal strength relies on the KOTO detector design, which consists of a calorimeter and a veto system. The calorimeter, made of a CsI array, is used to measure the incident photon energies and positions. The veto system enclosing the entire decay region is used to maximize the detection against the extra particles from backgrounds. These features enabled the search for the dark particle pair in K_L^0 decays at KOTO.

The $K_L^0 \to XX$ measurement was based on the data collected in June 2018 with the following two-level trigger criteria [3]: the first level trigger required that the energy sum in the calorimeter was larger than 550 MeV and no coincident hit was observed in the rest of the detector. The second level trigger required that the number of hits in the calorimeter was equal to four.

The blind analysis strategy was not applied to this study because of the limited and well-known background sources. The selection cuts were determined after the agreement between data and simulation was confirmed.

2. Reconstruction and event selection

A signal required exactly four photon clusters in the calorimeter. The K_L^0 decay vertex was obtained by exploiting that the invariant mass of the four photons was equal to the nominal K_L^0

mass ($M_{K_L^0}$) [4]. The two X masses (M_X) were subsequently calculated for the three possible pairings. The pairing that had the smallest difference between two M_Xs (ΔM_X) was selected.

The background reduction was studied by the Monte Carlo (MC) simulation using GEANT4 [5]. The $K_L^0 \to 3\pi^0$ decay became a background if the two extra photons were not detected. A photon was missed if a particle passed through a detector without adequate energy deposit, or if two hits in the calorimeter were close to each other and hence merged into one fused cluster (defined as a fusion cluster).

The $K_L^0 \to 3\pi^0$ background was highly suppressed after requiring no hit in the veto system. However, the $K_L^0 \to 3\pi^0$ decay has a large branching fraction of 0.2. An additional reduction by the kinematic cuts and cluster shape cuts was necessary. Because the $K_L^0 \to 3\pi^0$ background tends to have two different reconstructed M_Xs, the ΔM_X was required to be less than 10 MeV/c^2. A fusion cluster tends to have a larger cluster size than a single photon cluster. The cluster size was measured by the energy-weighted average of the distance between crystals and the hit position. The cluster size was required to be less than 40 mm. The shower shape was also used to distinguish a fusion cluster from a single photon cluster. Given the incident angle and the energy of a photon, the mean and the standard deviation of the energy deposit in each crystal were obtained. The χ^2 test (shape-χ^2) was then performed to evaluate if a cluster was induced by a single photon hit, and the shape-χ^2 was required to be less than 7.

After imposing all the cuts mentioned above, the remaining $K_L^0 \to 3\pi^0$ events had two fusion clusters. The three photon pairs are denoted by (γ_1, γ_2), (γ_3, γ_4), and (γ_5, γ_6). The four measured cluster energies, denoted by E_A, E_B, E_C, and E_D, are induced by

$$E_A = E_{\gamma_1}, \quad E_B = E_{\gamma_2} + E_{\gamma_3}, \quad E_C = E_{\gamma_4} + E_{\gamma_5}, \quad E_D = E_{\gamma_6}. \tag{1}$$

The three π^0 decays imply the following two constraints:

$$2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{\gamma_1\gamma_2}) = 2E_{\gamma_5}E_{\gamma_6}(1 - \cos\theta_{\gamma_5\gamma_6}), \tag{2}$$

$$2E_{\gamma_3}E_{\gamma_4}(1 - \cos\theta_{\gamma_3\gamma_4}) = M_{\pi^0}^2, \tag{3}$$

where $\theta_{\gamma_i\gamma_j}$ is the opening angle between γ_i and γ_j computed using the reconstructed K_L^0 vertex position. Therefore, the six photon energies can be solved explicitly. How likely an event was induced by such mechanism was evaluated by DF-Δm^2:

$$\text{DF-}\Delta m^2 = (M_{\gamma_1\gamma_2} - M_{\pi^0})^2 + (M_{\gamma_5\gamma_6} - M_{\pi^0})^2, \tag{4}$$

where $M_{\gamma_1\gamma_2}$ and $M_{\gamma_5\gamma_6}$ are the reconstructed invariant-mass values calculated in the left-hand side and the right-hand side of Eq. 2, respectively, and M_{π^0} is the nominal π^0 mass [4]. These calculations were performed for all the possible combinations of selecting two fusion clusters from the four clusters. The minimum of DF-Δm^2 among all the combinations was required to be larger than 1000 (MeV/c^2)^2.

The $K_L^0 \to \pi^0\pi^0$ decay is a special case of $M_X = M_{\pi^0}$. The two reconstructed M_Xs of $K_L^0 \to \pi^0\pi^0$ background are expected to be close to M_{π^0}. By requiring the average of the two M_Xs ($\overline{M_X}$) to be outside of the mass window of 120–150 MeV/c^2, 99.2% of the $K_L^0 \to \pi^0\pi^0$ events were suppressed. The remaining events had the property that the wrong pairing accidentally had the smallest ΔM_X, even though the correct pairing gave $M_X \approx M_{\pi^0}$. Hence, the diphoton invariant masses ($M_{\gamma\gamma}$) of the six possible pairings were calculated and the one that was closest to M_{π^0} was selected, as shown in Figure 1. The region of 120–150 MeV/c^2 was defined as the control region (CR). The signal was required to be outside of the CR.

The normalization of the MC to the data was performed using the CR after imposing all the selection criteria except for the DF-Δm^2 cut, and $N_{norm} = 11186$ events were observed in data. The acceptance was defined as the number of remaining events normalized to the number of K_L^0s

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entering the KOTO detector ($N_{K_L^0}$), and calculated using the MC. By exploiting the nominal $K_L^0 \to \pi^0\pi^0$ branching fraction [4], the $K_L^0 \to \pi^0\pi^0$ acceptance, and the N_{norm}, the $N_{K_L^0}$ in data was obtained.

Figure 2 shows the data distribution of K_L^0 decay vertex Z (Z_{vtx}) versus $\overline{M_X}$. The background events were suppressed in the upstream region. Therefore, the signal region was defined by Z_{vtx} < 2500 mm. No event was observed in the signal region. The number of $K_L^0 \to 3\pi^0$ background was predicted to be (0.61 ± 0.61), and the number of $K_L^0 \to \pi^0\pi^0$ background was predicted to be less than 0.62 at the 90% confidence level (C.L.). The gap of 120–150 MeV/c^2 was caused by the $K_L^0 \to \pi^0\pi^0$ background suppression. The gap of 160–190 MeV/c^2 was caused by the DF-Δm^2 cut.

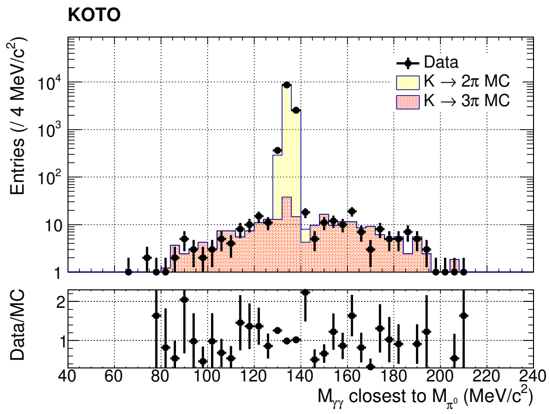

Figure 1. Distribution of the $M_{\gamma\gamma}$ that is closest to the nominal π^0 mass after imposing all the cuts against the $K_L^0 \to 3\pi^0$ background except for the DF-Δm^2 cut.

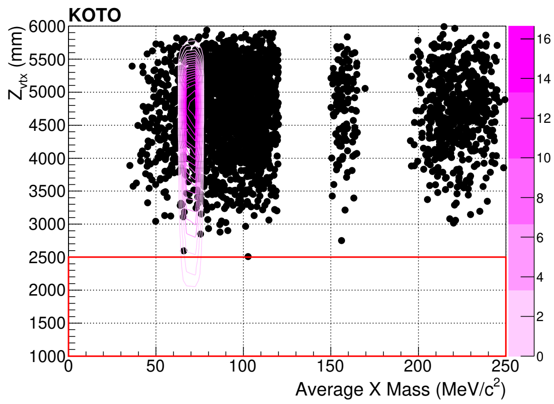

Figure 2. Distribution of Z_{vtx} versus $\overline{M_X}$. The thick red box represents the signal region. The dots indicate the data and the magenta lines indicate $K_L^0 \to XX$ signal contours for $M_X = 70$ MeV/c^2. The color code along the vertical axis indicates the number of signals assuming the branching fraction of 1×10^{-6}.

3. Result

The single event sensitivity (SES) was estimated to be $SES = 1/(N_{K_L^0} \times A_{sig})$, where A_{sig} is the signal acceptance. The A_{sig} was estimated by the MC as shown in Figure 3, and its statistical and systematic uncertainties were estimated to be 0.9% and 14.3%–46.9%, respectively. The variation in the systematic uncertainties was from the MC statistics, which depends on the M_X. Because the signal acceptances differed by more than $\mathcal{O}(10^3)$, the MC statistics uncertainty varied from 1.4% to 44.7%. The branching fraction was estimated by Poisson statistics with the coordination of systematic uncertainty fluctuations [6]. Figure 4 shows the upper limits of $\mathcal{B}(K_L^0 \to XX)$ at the 90% C.L. versus M_X.

4. Conclusion

The first search for the dark particle pair produced in K_L^0 decays was performed at KOTO. We assumed that the dark particle promptly decayed into two photons. After imposing all the selection criteria, the number of background events was predicted to be (0.61 ± 0.61). No signal was observed. For M_X ranging from 40 MeV/c^2 to 110 MeV/c^2, $\mathcal{B}(K_L^0 \to XX) < (1\text{–}4) \times 10^{-7}$ (90% C.L.) was set. For M_X ranging from 210 MeV/c^2 to 240 MeV/c^2, $\mathcal{B}(K_L^0 \to XX) < (1\text{–}2) \times 10^{-6}$ (90% C.L.) was set.

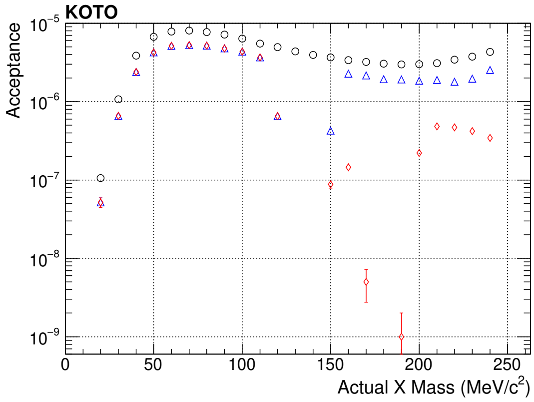

Figure 3. Signal acceptance versus M_X. The red diamond, blue triangle, black circular markers indicate the acceptance after imposing all the selection criteria, all but the DF-Δm^2 cut, and further excluding the cuts against the $K_L^0 \rightarrow \pi^0\pi^0$ background, respectively.

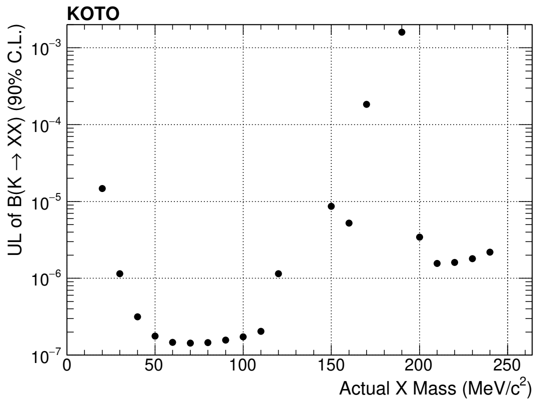

Figure 4. Upper limits of $\mathcal{B}(K_L^0 \rightarrow XX)$ for different X masses at the 90% confidence level.

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