Introduction. The $K_L \to \pi^0 \nu \overline{\nu}$ decay is a CP-violating process and is highly suppressed in the Standard Model (SM) due to the $s \to d$ flavor-changing neutral current transition [1, 2]. The branching fraction for this decay can be accurately calculated, and is one of the most sensitive probes to search for new physics beyond the SM (see, e.g., [3–10]). The SM prediction is $(3.00 \pm 0.30) \times 10^{-11}$ [11], while the best upper limit was $2.6 \times 10^{-8}$ (90% C.L.) [12] set by the KEK E391a experiment [13]. An indirect upper limit, called the Grossman-Nir bound [14], of $1.46 \times 10^{-9}$ is based on the $K^+ \to \pi^+ \nu \overline{\nu}$ measurement by the BNL E949 experiment [15].

The KOTO experiment [16, 17] at the Japan Proton Accelerator Research Complex (J-PARC) [18] is dedicated to study the $K_L \to \pi^0 \nu \overline{\nu}$ decay. The first physics run was conducted in 2013 and achieved a comparable sensitivity to E391a with 100 hours of data taking [19]. KOTO is also sensitive to the $K_L \to \pi^0 X^0$ decay [20, 21], where $X^0$ is an invisible light boson. The upper limit for this decay was set, for the first time in [19], as $3.7 \times 10^{-8}$ (90% C.L.) for the $X^0$ mass of 135 MeV/c^2.

Experimental methods and apparatus. A 30-GeV proton beam extracted from the J-PARC Main Ring with a duration of 2 seconds struck a gold production target [22], and secondary neutral particles produced at an angle of 16° from the proton beam were transported via the “KL beam line” [23] to the experimental area. The neutral beam, composed of neutrons, photons, and $K_L$'s, was collimated by two collimators made of iron and tungsten to a size of $8 \times 8$ cm^2 by the end of the 20-meter-long beam line. Neutrons scattered by the collimators outside the nominal solid angle of the beam are referred to as “halo-neutrons”. The collimators were aligned with a beam profile monitor [24] to minimize the halo-neutrons.

A schematic view of the KOTO detector is shown in Fig. 1. The origin of the z-axis, which lay along the
beam-direction, was the upstream edge of FB, 21.5 m away from the target. The x (horizontal) and y (vertical) axes were defined as in the right-handed coordinate system. The KOTO detector consisted of the CsI calorimeter (CSI) and hermetic veto counters around the decay volume in vacuum. The signature of the $K_L \to \pi^0 \nu \bar{\nu}$ decay was “two photons + nothing else”; we measured two photons from a $\pi^0$ decay with CSI and ensured that there were no other detectable particles in CSI and veto counters. The CSI was composed of 2716 undoped CsI crystals whose length was 50 cm and cross-section was $2.5 \times 2.5 \text{ cm}^2 (5 \times 5 \text{ cm}^2)$ within (outside) the central 1.2 $\times$ 1.2 m$^2$ region. The 15 $\times$ 15 cm$^2$ region at the center of CSI was the beam hole to let the beam particles pass through. The veto counters consisted of lead-scintillator sandwich, lead-aerogel, or undoped-CsI counters for photons and plastic-scintillators or wire chambers for charged particles. The waveform of the signal from all of the detector components was recorded either with 125-MHz digitizers after a Gaussian shaper circuitry [25] or 500-MHz digitizers [26]. Details of the detector components and new components after the 2013 run are explained in [17, 19, 27].

Data taking. This Letter is based on the data set collected in 2015 corresponding to $2.2 \times 10^{19}$ protons on target. The power of the primary proton beam increased from 24 kW to 42 kW during the period. The data acquisition system was triggered by two stages of trigger logic [28, 29]. The first-level trigger (L1) required energy deposition larger than 550 MeV in CSI and the absence of energy deposition in four veto counters which surrounded the decay volume (MB, CV, NCC, and CC03 in Fig. 1) using loose veto criteria. The second-level trigger (L2) calculated the center of energy deposition (COE) in CSI and required the distance from the beam center ($R_{\text{COE}}$) to be larger than 165 mm. L2 was implemented to reduce the contamination of the $K_L \to 3\pi^0$ decay with small missing energy. We collected 4.31 billion events for the signal sample with these trigger requirements. We simultaneously collected samples of $K_L \to 3\pi^0$, $K_L \to 2\pi^0$, and $K_L \to 2\gamma$ decays for the purpose of normalization and calibration by disregarding the L2 decision (and without veto requirements in the L1 decision) with a prescaling factor of 30 (300).

Reconstruction and event selection. The electromagnetic shower generated by a photon in CSI was reconstructed using a cluster of hits in adjacent crystals with energies larger than 3 MeV. A $\pi^0$ was reconstructed from two clusters in CSI assuming the $\pi^0 \to 2\gamma$ decay. The opening angle, $\theta$, of the two photons was calculated with $\cos \theta = 1 - M_\pi^2/(2E_{\gamma_1}E_{\gamma_2})$, where $M_\pi$ is the nominal $\pi^0$ mass, and $E_{\gamma_1}$ and $E_{\gamma_2}$ are the energies of two photons. The $\pi^0$ decay vertex ($Z_{\text{vtx}}$) and transverse momentum ($P_t$) were calculated assuming that the vertex was on the beam axis. In the case of the $K_L \to \pi^0 \nu \bar{\nu}$ decay, the reconstructed $\pi^0$ should have a finite $P_t$ due to the two missing neutrinos. Signal candidates were required to have $Z_{\text{vtx}}$ in the range of $3000 < Z_{\text{vtx}} < 4700$ mm to avoid $\pi^0$’s generated by halo-neutrons hitting detector components. This requirement let 3.2% of the $K_L$’s entering the detector at the end of the beam line decay. The candidates were also required to have a $P_t$ in the range of $P_{\text{min}} (Z_{\text{vtx}}) < P_t < 250 \text{ MeV}/c$, where $P_{\text{min}} (Z_{\text{vtx}})$ was 130 MeV/c in the range of $3000 < Z_{\text{vtx}} < 4000$ mm and varied linearly from 130 MeV/c to 150 MeV/c in the range of $4000 < Z_{\text{vtx}} < 4700$ mm. This requirement on $P_t$ greatly suppressed events from the $K_L \to \pi^+\pi^−\pi^0$ decay.

A series of selection criteria (cuts) based on the energy, timing, and position of the two clusters in CSI were imposed on the candidates. We determined all the cuts without examining events inside the region $2900 < Z_{\text{vtx}} < 5100$ mm and $120 < P_t < 260 \text{ MeV}/c$. In order to ensure the consistency with trigger conditions, we required $E_{\gamma_1} + E_{\gamma_2} > 650 \text{ MeV}$ and $R_{\text{COE}} > 200$ mm. For each reconstructed photon, we required $100 < E_{\gamma} < 2000$ MeV and the hit position $(x, y)$ to be in the CSI fiducial region of $\sqrt{x^2 + y^2} < 850$ mm and $\min(|x|, |y|) > 150$ mm (photon selection cuts). The following kinematic cuts on the two photons in CSI were imposed. Consistency of the timing of two photons, after taking into account the time-of-flight from the $\pi^0$ decay vertex to CSI, was required to be within 1 ns of each other. The distance between the two clusters was required to be larger than 300 mm to ensure a clean separation. To avoid mis-measurement of photon energies due to three dead channels in CSI, the position of clusters was required to be more than 53 mm apart from those channels. The ratio of the energy of two photons, $E_{\gamma_2}/E_{\gamma_1}$ ($E_{\gamma_1} > E_{\gamma_2}$), was required to be larger than 0.2 to reduce a class of the $K_L \to 2\pi^0$ background originating from mis-combinations of two photons in the $\pi^0$ reconstruction. For the same purpose, the product of the energy and the angle between the beam axis and the momentum of a photon was required to be larger than 2500 MeV·deg. The opening angle of two photons in the x-y plane was required to be smaller than $150^\circ$ to reduce the $K_L \to 2\gamma$ background, in which the photons are back-to-back. To select $\pi^0$ candidates with plausible kinematics, allowed regions were set on $P_t/P_z - Z_{\text{vtx}}$ and $E - Z_{\text{vtx}}$ planes, where $P_z$ and $E$ are the longitudinal momentum and energy of the $\pi^0$, respectively. This cut was effective in reducing the “CV-$\eta$ background” which is described later. Events were rejected if there were any hits in the veto counters coincident with the $\pi^0$ decay. Cluster-shape and pulse-shape cuts in the CSI (shape-related cuts), defined later, were also imposed on the photons from $\pi^0$ candidates to reduce the background from photon-cluster fusion and neutron showers.

The signal acceptance $A_{\text{sig}}$ was evaluated using GEANT4-based [30–32] Monte Carlo (MC) simulations. Accidental activities in the KOTO detector were taken into account by overlaying random trigger data collected during the data taking. The $A_{\text{sig}}$ was calculated at 0.52%
after convoluting the reduction from kinematic (57%), veto (17%), and shape-related (52%) cuts. The data reduction is summarized in Table I.

### Table I. Data reduction in each of the selection criteria.

| Selection criteria                     | Number of events |
|----------------------------------------|------------------|
| Triggered events                       | $4.31 \times 10^9$ |
| Two clusters                           | $8.74 \times 10^8$ |
| Trigger-related cuts                   | $2.50 \times 10^8$ |
| Photon selection cuts                  | $1.75 \times 10^8$ |
| Kinematic cuts                         | $3.59 \times 10^7$ |
| Veto cuts                              | $3.83 \times 10^4$ |
| Shape-related cuts                     | 347              |

The single event sensitivity (SES) for the $K_L \to \pi^0 \nu \bar{\nu}$ decay was obtained to be

$$\text{SES} = \frac{1}{A_{\text{sig}}} \frac{A_{\text{norm}} \cdot \text{Br}(K_L \to 2\pi^0)}{p \cdot N_{\text{norm}}},$$

where $A_{\text{norm}}$ is the acceptance for $K_L \to 2\pi^0$ evaluated based on MC simulations, $\text{Br}(K_L \to 2\pi^0)$ is the branching fraction of $K_L \to 2\pi^0$ [12], $p$ is the prescale factor of 30 used to collect the $K_L \to 2\pi^0$ sample, and $N_{\text{norm}}$ is the number of reconstructed $K_L \to 2\pi^0$ events in the data after subtracting the $K_L \to 3\pi^0$ contamination. Based on $A_{\text{norm}} = 0.36\%$ and $N_{\text{norm}} = 1.52 \times 10^4$, the SES was evaluated to be $(1.30 \pm 0.01_{\text{stat.}} \pm 0.14_{\text{syst.}}) \times 10^{-9}$. The sensitivity is almost an order of magnitude better compared to that of E391a [13] and KOTO’s first results [19], and comparable to the Grossman-Nir bound. The expected number of the SM signal events is 0.023 in this analysis.

The systematic uncertainties in the SES are summarized in Table II. The major sources of the uncertainty were the kinematic cuts for the $K_L \to \pi^0 \nu \bar{\nu}$ selection, the shape-related cuts, and the consistency among the normalization decays $K_L \to 2\pi^0$, $K_L \to 3\pi^0$, and $K_L \to 2\gamma$. The former two were evaluated as follows. A sample of $\pi^0$'s from the reconstructed $K_L \to 2\pi^0$ events was used as a validation sample. The discrepancy between data and MC acceptance, defined as $(A_{\text{MC}} - A_{\text{Data}}^i)/A_{\text{Data}}^i$, where $A_{\text{Data(MC)}}^i$ represents the acceptance of $i^{th}$ cut for data...
Two-cluster events were selected in this control sample with selection criteria similar to those used for the signal sample. Two types of cuts were used to reduce the contamination from these neutron-induced events based on cluster shape discrimination [34] and pulse shape discrimination [35]. A photon-like cluster was selected by considering several variables based on an electromagnetic shower library produced by the MC simulation. The variable with the most discriminating power between photon and neutron clusters was an energy-based likelihood calculated using the accumulated energy distribution in each crystal as a probability density function. Additional variables, such as global energy and cluster timing information, were used in minimum chi-square estimations and combined with the energy-based likelihood as inputs to a neural network [36] with a single output variable able to distinguish between electromagnetic and hadronic cluster hypotheses. The pulse shape discrimination used the waveform of read-out signal from each CSI crystal. The waveform was fitted to the following asymmetric Gaussian:

\[ A(t) = |A| \exp \left( -\frac{(t-t_0)^2}{2\sigma(t)^2} \right) , \]  

where \( \sigma(t) = \sigma_0 + a(t-t_0) \) depends on the timing difference from the mean of the Gaussian \( (t_0) \). Using templates of the fit parameters, \( \sigma_0 \) and \( a \), obtained in a hadron-cluster control sample and by a photon sample from \( K_L \rightarrow 3\pi^0 \), a likelihood ratio was calculated to determine which of the hadron-cluster and the two-photon event was more likely to be. We evaluated the rejection power of cuts based on these two discrimination variables for the Al-plate control sample by taking their correlation into account. The number of the background events was normalized by comparing the numbers of events of the signal sample and of the control sample outside the signal region before imposing these cuts. The number of the background events was estimated to be 0.24. Note that this is an overestimate due to kaon contamination in the control sample, which we were unable to subtract quantitatively from the estimation because of the limited statistics.

The background called “upstream-\( \pi^0 \)” was caused by halo-neutrons hitting the NCC counter in the upstream end of the decay volume and producing \( \pi^0 \)’s. The reconstructed \( Z_{\text{vtx}} \) for such decays is shifted downstream into the signal region if the energies of photons were mis-measured to be smaller due to photo-nuclear interactions in CSI, or if one photon in the CSI is paired to a secondary neutron interacting in the CSI to reconstruct the \( \pi^0 \). This background was evaluated by simulation, and the yield was normalized to the number of events in the upstream region in the data and MC. We estimated the number of this background to be 0.04.

The background called “CV-\( \eta \)” stemmed from the \( \eta \) production in the halo-neutron interaction with CV [37],
Considered the upper limit for the branch in Fig. 3. Assuming Poisson statistics with uncertainties posed, no signal candidate events were observed as shown be 0.04.

The number of the background events was estimated to when a halo-neutron hit CV and produced an particles located in front of CSI. In this background, which was a veto counter of plastic scintillator for charged particles located in front of CSI. In this background, when a halo-neutron hit CV and produced an η meson, and the two photons from the η decay hit CSI, the two clusters were reconstructed using the π0 mass hypothesis which pushes the reconstructed Z_vtx upstream into the signal region. This background was suppressed by imposing a cut which evaluates the consistency of the shape of the clusters with the incident angle of the photons originated from the η → 2γ decay produced at CV. The number of the background events was estimated to be 0.04.

Conclusions and prospects. After all the cuts were imposed, no signal candidate events were observed as shown in Fig. 3. Assuming Poisson statistics with uncertainties taken into account [38], the upper limit for the branching fraction of the K_L → π^0νττ decay was obtained to be 3.0 × 10^{-9} at the 90% C.L. The upper limit for the K_L → π^0X^0 decay was also set to be 2.4 × 10^{-9} (90% C.L.) for m_{X^0} = m_{π^0}. These results improve the upper limit of the direct search by almost an order of magnitude.

Based on this analysis, we developed necessary measures to reach better sensitivity. We anticipate to improve background rejection with data collected after 2015 with a newly-added veto counter in 2016 [39] and more refined analysis methodologies, exploiting the substantially higher statistics of the collected control samples.

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