PROCEEDINGS OF SCIENCE

Search for the rare decay of $K_L^0 \to \pi^0 \nu \bar{\nu}$ with the KOTO detector

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The goal of the J-PARC KOTO experiment is to observe the $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay and measure its branching ratio. The prediction for the branching ratio from Standard Model (SM) processes is 3.0 x 10^{-11} with a theoretical uncertainty of 2.5%. The previous experimental limit is 2.6 x 10^{-8}, set by the KEK E391a collaboration [J. Ahn et al., Phys. Rev. **D81**, 072004 (2010)]. A comparison of experimentally obtained results with SM calculations permits a test of the quark flavor region and is an ideal candidate to search for Physics Beyond the SM (BSM). Despite the success of the KEK E391a collaboration, it highlighted the need for further upgrades with the anticipated increase of beam power at the J-PARC 30 GeV proton accelerator, and motivated the development of the KOTO detector. A characteristic of the process of interest is a pair of photons from the π^0 decay and no other detected particles. KOTO uses a Cesium Iodide (CsI) electromagnetic calorimeter as the main detector to measure the energies and positions of the two photons, and hermetic veto counters to guarantee that there is no other detectable particle. The first data was collected in spring 2013, and since then we have had four additional data runs in 2015−2016 at beam powers of roughly 24 and 39 kW, respectively. In this report, we present results of the first search with KOTO, a description of the upgrades to the detector, and the current status of the analysis with the aim to reach the sensitivity of the Grossman-Nir bound [Y. Grossman;..et al.: Adv. Ser. Direct. High Energy Phys.**15**:755-794, (1998)] for the larger 2015−2016 data.

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1. Introduction and motivation

CP violation has been acknowledged as an integral part to deepening our understanding of particle physics and presently, along with investigating unresolved questions regarding neutrinos, is a growing topic of study. The rare decay, $K_L^0 \to \pi^0 \nu\bar{\nu}$, of the neutral kaon is a direct CP-violating process, and is one of the most sensitive probes to search for new physics beyond the Standard Model (SM) of particle physics. Because this decay proceeds by a Flavor Changing Neutral Current (FCNC) from a strange to a down quark (s→ d), and is suppressed in the SM, it has been deemed a *golden* mode that permits testing of SM [3].

The SM predicts the branching fraction (Br) for $K_L^0 \to \pi^0 \nu\bar{\nu}$ to be (3.00 ± 0.30) x 10^{-11}, while the current experimental upper limit is 2.6 x 10^{-8} at the 90% confidence level (C.L.) set by the KEK E391a experiment [4]. The BNL E949 experiment has set an indirect and model-independent limit Br ($K_L^0 \to \pi^0 \nu\bar{\nu}$) < 1.46 x 10^{-9} based on the measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching fraction. Although $K_L^0 \to \pi^0 \nu\bar{\nu}$ is an extremely rare decay, it offers one the best methods for investigating CP violation in the quark sector. If the measured Br deviates from the prediction, it indicates physics BSM. Presently, there is a mirror search conducted at CERN, the NA62 experiment, involving charged kaon decays ($K_L^+ \to \pi^+ \nu\bar{\nu}$) [6]. A combination of both results is vital to developing a better understanding of the underlying CP violating process, where the KOTO results will place limits on the height of the unitary triangle. This highlights the growing interest and importance of investigating rare decay processes.

2. KOTO Experiment

2.1 KOTO detector

The experiment was conducted at the Hadron Experimental Facility (HEF) of J-PARC. A beam of 30-GeV protons was slowly extracted from the Main Ring (MR) and impinged on a 66-mm-long gold target at HEF. The generated kaons were selected at a 16 degree angle from the primary proton beam through a neutral beam line consisting of a pair of collimators composed of iron and tungsten, a sweep magnet, and a 7 cm-thick lead photon absorber. The neutral beam after collimation had a solid angle of 7.8 μsr, and a size of 8 x 8 cm^2 at roughly 20 m downstream from the target. The K_L momentum peaked at around 1.4 GeV/c. The neutral beam was known to also contain photons and neutrons. We designated neutrons located outside the nominal beam solid angle as *halo neutrons*, which originated from scattering inside the collimators. A cross-sectional side view detector system is shown in Fig. 1. The decay volume along the beam line within the detector was expected to be about 3 m long. Two photons from a π^0 decay were detected by the electromagnetic calorimeter. It consisted of 2716 undoped Cesium Iodide (CsI) crystals, stacked inside a 1.9 m diameter cylinder, excluding the most central 20 x 20 cm^2 region.

2.2 Experimental method

The signature of the $K_L^0 \to \pi^0 \nu\bar{\nu}$ decay is a single π^0 from a K_L decay without any other detectable particles, in which the two photons from the π^0 have a discernible, large, transverse momentum. The CsI calorimeter measures the energies and positions of the two photons, and hermetic veto counters are used guarantee that there is no extra charged particle or photons at the

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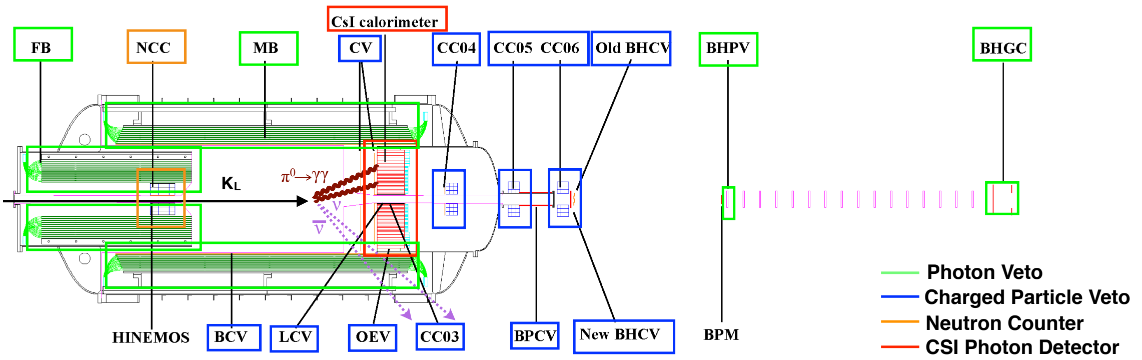

Figure 1: (Color online) Cross-sectional side view of the KOTO detector. The beam enters from the left hand side and lies along the z axis.

trigger level. Among K_L^0 decay modes, only $K_L^0 \to \pi^0 \nu \bar{\nu}$ and $K_L^0 \to \gamma\gamma$ are able to produce two photons and no other charged particles in the final state. This clean mode of decay does have some difficulties in experimentally being observed. A principal challenge of the study is the reduction of background from other K_L^0 decays, such as $K_L \to \pi^0 \pi^0$, $K_L \to \pi^+ \pi^- \pi^0$, as well as hadronic shower events in the CsI stemming from *halo neutron* induced interactions.

3. Results

The collaboration performed a search for $K_L \to \pi^0 \nu \bar{\nu}$, with the initial physics data taken in 2013. The run was limited to only 100 hrs of recorded data due to an accelerator failure. In the left panel in Fig. 3, the accumulated protons on target (POT) for the experimental runs and the corresponding beam power are given on the left and right vertical axis, respectively. The reconstructed pion transverse momentum (P_t) vs reconstructed decay vertex (right) for candidate events from the 2013 data set is shown in Fig. 3 for the first physics run. The smaller rectangular area is the $K_L^0 \to \pi^0 \nu \bar{\nu}$ signal box. Expectations of events for data and Monte-Carlo in different regions are shown as the black and red numbers, respectively in the figure. From our blind analysis there was one event observed with the expectation of 0.34 ± 0.16 background events. This allowed the collaboration to set an upper limit of 5.1 x 10^{-8} for the branching fraction at the 90% confidence level (C.L.) [5]. A summary of estimated background events in the signal region are listed in Table 1.

Table 1: Summary of estimated background events in the signal region

Source of background	Estimated events
K_L^0 decay events	0.10 ± 0.04
Halo neutron events on CsI	0.18 ± 0.15
Halo neutrons events on NCC	0.06 ± 0.06
Total	0.34 ± 0.16

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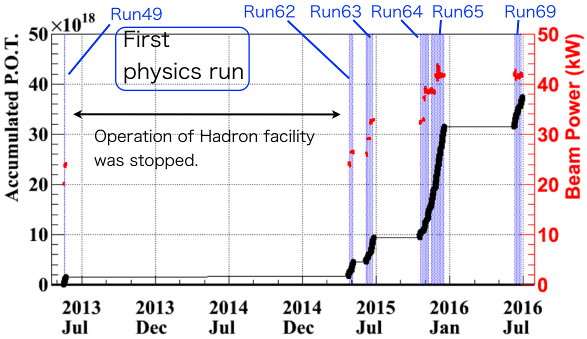

Figure 2: (Color online) Accumulated Protons on Target (POT) since the launch of the KOTO experiment is shown on the left axis. The right axis shows the associated beam power for each run.

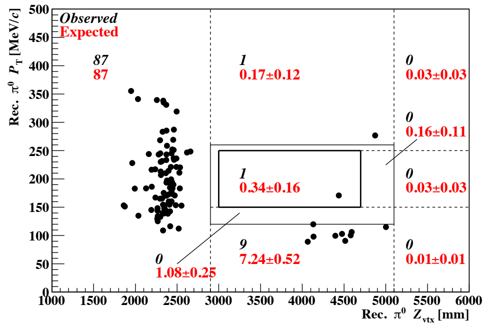

Figure 3: (Color online) Neutral pion P_t vs reconstructed decay vertex for candidate events from the 2013 data set. The smaller rectangular area is the $K_L^0 \to \pi^0 \nu \bar{\nu}$ signal box. Expectations of events for data and Monte-Carlo in different regions are shown as the black and red numbers, respectively.

3.1 Upgrades

The main background contributions in the signal region came from halo neutron events, $K_L \to \pi^0 \pi^0$, and $K_L \to \pi^+ \pi^- \pi^0$, where the neutron struck the CsI and the resulting showers mimicked two photon events. In the other cases, charged particles and extra photons went undetected or escaped through the beam hole located at the center of the CsI resulting in only two photon events being detected. To reduce these events we have included the following veto detectors: the Inner Barrel (IB), the Beam Hole Charge Veto (BHCV), the Beam Hole Photon Veto (BHPV), and the Beam Hole Guard Counter (BHGC). Additional upgrades to the data acquisition system (DAQ) are in progress.

4. Summary and Outlook

The data taken during experimental runs of fall 2015 (Runs 62−65) and summer 2016 (Run 69) when completely analyzed are expected to be at the sensitivity of the Grossman-Nir Bound [2]. In Fig. 4, the reconstructed π^0 P_t vs decay vertex for candidate events from Run 62 are shown. The shaded rectangular area is the $K_L^0 \to \pi^0 \nu \bar{\nu}$ blinded signal box. Expectations of background events for data and Monte-Carlo are shown as the black and red numbers, respectively in the figure. A listing of the estimated background contributions and sources are provided in Table 2.

We have continued the search for $K_L^0 \to \pi^0 \nu \bar{\nu}$ with the KOTO detector. From the analysis of data gathered in 2013 there was one event observed with the expectation of 0.34 ± 0.16 background events. As a result, we were able to set an upper limit for the branching fraction of 5.1 x 10^{-8} at a 90% confidence level (C.L.). We continued the effort to search for this rare decay by making improvements that included upgrades to the data acquisition system and the addition of veto detectors. Since restarting the search in 2015, we have taken roughly 20 times more data than the initial 2013 run. Our objectives are to continue analyzing the K_L^0 events from the normalization modes ($K_L^0 \to \pi^0 \pi^0 \pi^0$, $K_L^0 \to \pi^0 \pi^0$, and $K_L^0 \to \gamma\gamma$) in order to determine the K_L^0 flux and normal-

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ize the single event sensitivity, and improve cut selections in order to further reduce background contributions.

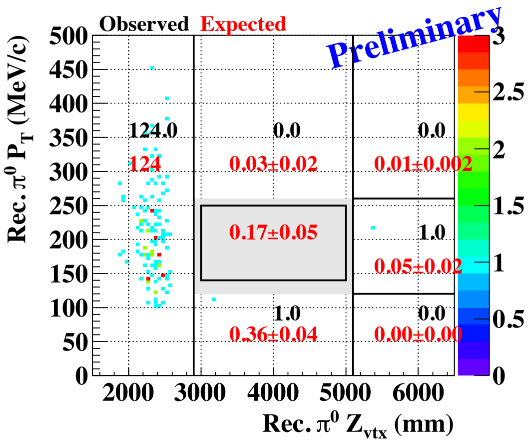

Figure 4: (Color online) Plot of reconstructed P_t vs reconstructed decay vertex for candidate events from the 2015 data set with kinematic and veto cuts applied. The shaded rectangular area is the $K_L^0 \to \pi^0 \nu \bar{\nu}$ blinded signal box. Observed events for data and expectations from Monte-Carlo in different regions are shown as the black and red numbers respectively in the figure.

Table 2: Preliminary summary of estimated background events in the signal region

Source of background	estimated events
$K_L^0 \to \pi^0 \pi^0$	0.04 ± 0.03
$K_L^0 \to \pi^0 \pi^+ \pi^-$	0.04 ± 0.03
Halo neutron events on CsI	0.05 ± 0.03
Halo neutrons events on NCC	0.04 ± 0.03
Total	0.17 ± 0.05

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