4.2

First strains of KOTO from J-PARC: Exploring new physics through rare kaon decays

An international collaboration consisting of 65 physicists from Japan, Korea, Russia, Taiwan, and USA has published the first physics results [1] from their experiment KOTO, short for “K0 at Tokai”, and continues to make strides toward exploring new physics beyond the Standard Model (SM) through rare K meson (kaon) decays. The experiment is being conducted at the Hadron Experimental Facility of J-PARC using the slowly extracted high intensity protons with an energy of 30 GeV from the Main Ring accelerator.

The quantum transition of a heavy particle into lighter particles is called “decay” in particle physics. The decay of particle proceeds via several paths or “decay modes”. The KOTO experiment studies the decay of the long lived neutral kaon (K_L) into a neutral pi meson (π^0) and a pair of neutrinos, represented as $K_L \rightarrow \pi^0\nu\bar{\nu}$. This decay occurs due to higher order effects in the neutral current from strange to down quark, and breaks the symmetry in the combination of charge conjugation and spatial inversion, CP symmetry, directly. The SM predicts the branching fraction Br ($K_L \rightarrow \pi^0\nu\bar{\nu}$), once in forty billion K_L decays, very precisely. By examining this ultra-rare decay, new sources of CP symmetry breaking that can explain the matter-antimatter asymmetry in the universe may be revealed most clearly, particularly in the case where the measured Br ($K_L \rightarrow \pi^0\nu\bar{\nu}$) is much higher than the predicted one. In reality, this decay mode occurs with only two photons from the subsequent π^0 decay detectable in the final state and has so far never been detected experimentally.

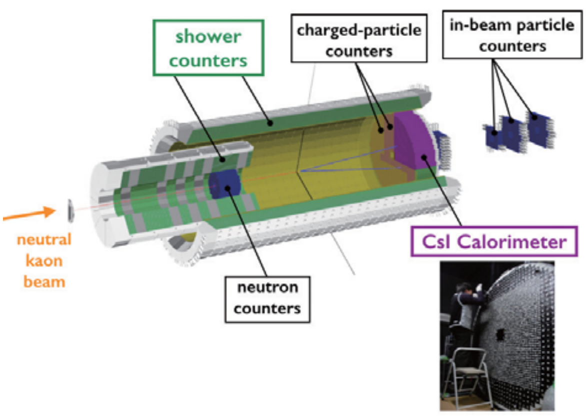

Fig. 1. Schematic drawing of the detector for the KOTO experiment.

The KOTO experiment, proposed in 2006 and approved in 2009, is the only experimental study of the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay in the world. The neutral beam line and the detector (Fig. 1) were constructed from FY2009 to FY2012 and the data collection started in May 2013. The crucial feature of the detector employed is the calorimeter at the endcap and the use of 50 cm long undoped CsI crystals to measure two photons from π^0. The 2,716 crystals and phototubes were the ones used in the KTeV experiment at Fermilab, USA, in the 1990s. For hermetic detection of extra particles from K_L decay backgrounds, e.g. $K_L \rightarrow \pi^0\pi^0$ and $K_L \rightarrow \pi^0\pi^+\pi^-$, and vetoes on them, charged particle and electromagnetic shower counters were installed on the inside of the vacuum vessel of the detector, covering the K_L decay volume. Counters were also placed downstream of the vessel to detect particles escaping along the beam line.

The first physics results from KOTO are from the data collected over one hundred hours in 2013, corresponding to 1.6×10^{18} protons-on-target (POT). The single event sensitivity for $K_L \rightarrow \pi^0\nu\bar{\nu}$ is comparable to the final sensitivity of the previously performed E391a experiment [2] at the KEK Tsukuba campus

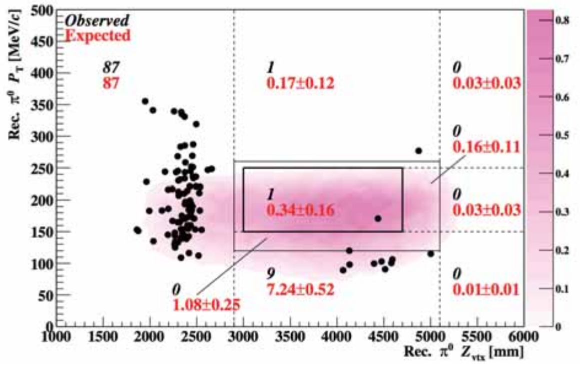

Fig. 2. Scatter plot summarizing the KOTO analysis for the first physics results [1].

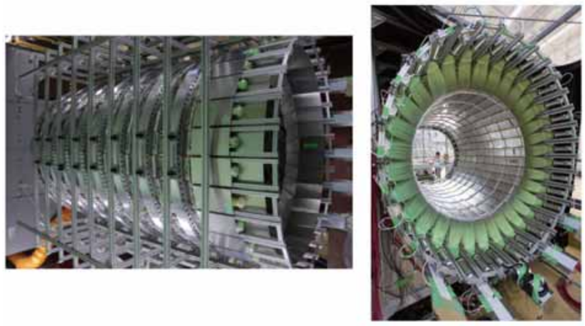

Fig. 3. Photographs of the IB shower counters.

in 2005, derived with 2.5×10^{18} POT with an energy of 12 GeV over four months. Figure 2 shows the scatter plot of the reconstructed π^0 transverse momentum (P_T) versus the decay vertex position (Z_{vtx}) of the events with all the selection criteria, including extra particle vetoes. The region surrounded with a thick solid line is the signal region, in which the $K_L \to \pi^0 \nu\bar{\nu}$ decay should appear as an event with a finite P_T, corresponding to the momentum taken away by two neutrinos, and with Z_{vtx} in the decay volume. The black dots represent the data, and the pink contour indicates the distribution of the $K_L \to \pi^0 \nu\bar{\nu}$ decay from Monte Carlo simulations. The black italic (red regular) numbers indicate the numbers of observed events (expected background events) for the regions divided by solid and dashed lines. One candidate event was observed while 0.34 ± 0.16 background events were expected, mainly due to halo neutrons in the beam directly hitting the calorimeter, and an upper limit of 5.1×10^{-8} for Br ($K_L \to \pi^0 \nu\bar{\nu}$) was set. The KOTO experiment also performed the direct search of the two-body decay $K_L \to \pi^0 X^0$, where X^0 is a hypothetical invisible particle [3] with a mass around the nominal π^0 mass, and an upper limit of 3.7×10^{-8} for Br ($K_L \to \pi^0 X^0$) was set for the first time.

KOTO resumed data taking in April 2015 and, in FY2015 and FY2016, collected twenty times more data than that of the first run. The analysis is currently undertaken intensively. In the meanwhile, large 3 m long shower counters (Fig. 3) with a diameter of 1.9 m and a weight of 6 tons in total, named "Inner Barrel (IB)", were built at the Tsukuba campus, transported to Tokai, and successfully installed to the KOTO detector in March 2016. The commissioning of the IB counters in FY2016 demonstrated that the counters would improve the veto capability of the KOTO detector and reduce the level of the $K_L \to \pi^0\pi^0$ background to be below Br ($K_L \to \pi^0 \nu\bar{\nu}$) in the SM, as designed.

Since 2013, KOTO collaborators have upgraded several detector subsystems and developed new analysis methods, particularly to discriminate photons from neutrons in the calorimeter, to reduce the backgrounds. The collaborators are also preparing to modify the calorimeter to add a neutron discrimination capability. With these improvements, they expect to continue the KOTO experiment to explore the wide region in Br ($K_L \to \pi^0 \nu\bar{\nu}$) to the level of SM prediction, and observe the $K_L \to \pi^0 \nu\bar{\nu}$ decay for the first time.

References

[1] J. K. Ahn *et al*., J-PARC KOTO Collaboration, Prog. Theor. Exp. Phys. **2017**, 021C01 (2017).

[2] J. K. Ahn et *al*., E391a Collaboration, Phys. Rev. D **81**, 072004 (2010).

[3] K. Fuyuto, W. S. Hou, M. Kohda et al., Phys. Rev. Lett. **114**, 171802 (2015).