

## Status and prospects of J-PARC KOTO experiment

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### Abstract

The J-PARC KOTO experiment was designed to observe the rare decay of long lived neutral kaons,  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ . The goal of KOTO is to observe the decay with the sensitivity of the Standard Model prediction, and search for new physics beyond the Standard Model. The KOTO apparatus consists of a high intensity  $K_L$  beam line, an electromagnetic calorimeter, and veto counters. The beam line and the calorimeter have already been built at J-PARC, and the veto counters are being constructed and tested for upcoming physics runs. In this paper, the KOTO experiment will be briefly introduced and the status and the prospects of the KOTO experiment will be described.

**Keywords:** new physics, Kaon,  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ , CP violation, KOTO experiment, BEACH 2012, proceedings

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### 1. Introduction

The KOTO experiment aims to observe a rare decay of long lived neutral kaons,  $K_L \rightarrow \pi^0 \nu \bar{\nu}$ . By observing the decay, we can search for new physics beyond the Standard Model (SM).

#### 1.1. Physics

In the SM, the decay process is mediated by the second order diagrams of the electroweak interactions with the flavor-changing neutral current process with three generations in the quark sector:  $s \rightarrow t \rightarrow d$ . The branching ratio of the  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay is proportional to  $\eta^2$  where  $\eta$  represents the imaginary part of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements in Wolfenstein's parametrization[1], which causes CP violation. One feature of this decay mode is that its calculated theoretical error is only 2%. The branching ratio of the  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay is predicted to be  $Br_{SM}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (2.43^{+0.40}_{-0.37} \pm 0.06) \times 10^{-11}$ [2], and the uncertainty is dominated by the currently measured CKM parameters.

If a non-SM particle propagates in the loop, the branching ratio of the  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay may be different from the SM prediction. Because the decay directly violates CP symmetry, the deviation of the branching

ratio from the SM prediction also implies new sources of the CP violation. There are some theoretical models of new physics beyond the SM which enhance the branching ratio of the decay.

The current upper limit of the branching ratio of the decay was set by KEK-PS E391a experiment, a pilot experiment of the KOTO experiment, to be  $2.6 \times 10^{-8}$  (90% C.L.)[3, 4]. There is another upper limit indirectly set by  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  isospin rotation, called Grossman-Nir bound[5], and measured to be  $1.4 \times 10^{-9}$  (90% C.L., by E787/E949 result[6]), about 2 orders of magnitude larger than the SM prediction. KOTO will explore the range between the Grossman-Nir bound and the SM prediction, and so search for new physics.

#### 1.2. Experimental method

A decay volume for  $K_L$  is surrounded by particle detectors. The signature of a  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay is that there are two photons from a  $\pi^0$  decay and no other visible particles in the final state. An electromagnetic calorimeter is placed downstream of the decay volume to detect the two photons. All the  $K_L$  decay modes except  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  and  $K_L \rightarrow \gamma \gamma$  have at least two charged particles, or two or more extra photons in the final state. These decays can be rejected by detecting additional

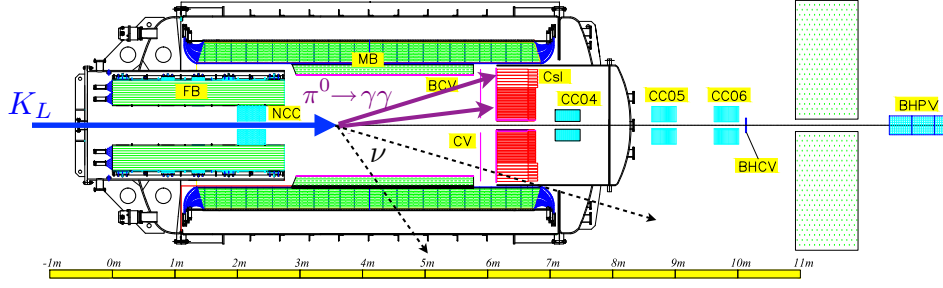


Figure 1: Side view of the KOTO detector. The decay volume in the middle of the detector is surrounded by hermetic particle detectors.

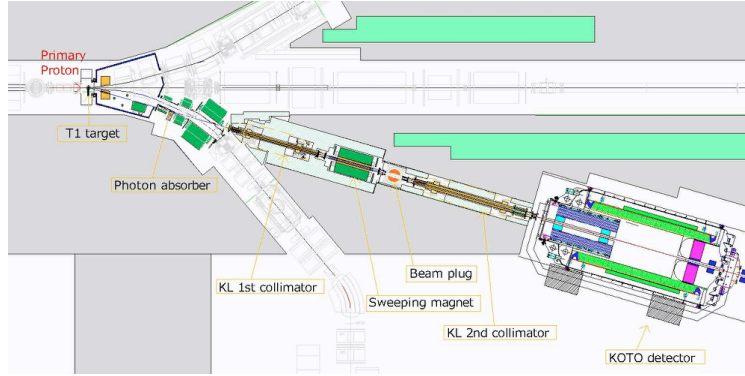


Figure 2: Schematic view of the neutral beam line.

particles with the surrounding detectors. The  $K_L \rightarrow \gamma\gamma$  decays can be rejected by requiring a finite transverse momentum for the two photon system. In the case of the  $K_L \rightarrow \pi^0\nu\bar{\nu}$  decay, the two photon system has a finite transverse momentum, because the undetected two neutrinos take some momentum away. We calculate the decay vertex and reconstruct the  $K_L \rightarrow \pi^0\nu\bar{\nu}$  decay from two photons in the calorimeter with the assumption that the two photons come from a  $\pi^0$  decay on the z-axis.

## 2. Apparatus and its status

Figure 1 shows a side view of the KOTO detector. We reuse the E391a detector with a number of upgrades. The apparatus of KOTO experiment is characterized by a high intensity  $K_L$  beam, a CsI calorimeter, veto detectors and a waveform digitization. In this section, we describe the apparatus and its status.

### 2.1. $K_L$ beam line

Figure 2 shows an overview of the beam line. The J-PARC main ring was designed to deliver 30 GeV protons to our experimental hall for 0.7 seconds out of every 3.3 seconds. The  $K_L$  particles are produced by the

primary protons striking a common target, and the  $K_L$  particles are transported through a neutral beam line to the KOTO detector. The target consists of five Ni disks with the total thickness of 53.9 mm. The neutral beam line is located at  $16^\circ$  from the primary proton beam in a horizontal plane. The beam line is 21 m long and consists of a pair of collimators, a sweeping magnet, and a  $\gamma$  absorber. The first collimator is 400 cm long, and the second collimator is 500 cm long. They are made of iron except for the 50 cm long region at the upstream end, which are made of tungsten. The magnet is placed between the two collimators to sweep out charged particles. The  $\gamma$  absorber is 7 cm long and made of lead.

The beam line construction was completed in 2009. We aligned the collimating system and measured the beam profile with the scintillating fiber hodoscope[7] in 2010 and 2011.

We also measured the number of  $K_L$ s produced per protons on target and their momenta, detecting two charged particles and two photons with hodoscopes and calorimeters, and reconstructing them by assuming that they were from  $K_L \rightarrow \pi^+\pi^-\pi^0$  decay. Figure 3 shows the invariant mass distribution and momentum spectra

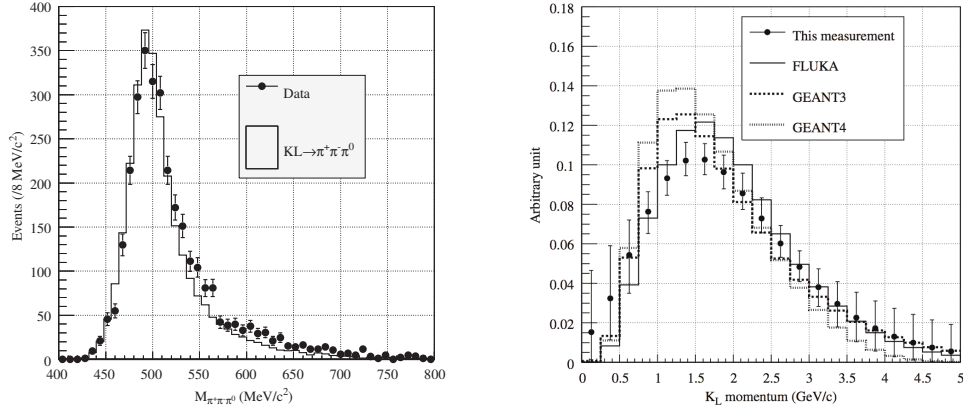


Figure 3: The observed invariant mass distribution (left) and momentum spectra at the exit of the beam line (right) of reconstructed  $K_L$ s[8].

of reconstructed  $K_L$ s at the exit of the beam line[8]. The measured  $K_L$  yield was 2.6 times higher than what was assumed in the proposal.

### 2.2. CsI calorimeter

The CsI electromagnetic calorimeter is placed downstream of the decay volume, as shown in Fig. 1, to measure energies, timings and incident positions of photons. To improve granularity and get more information on the shower shape for photons, 496 E391a crystals with the dimension of  $7 \times 7 \times 30 \text{ cm}^3$  were replaced by 2240 crystals with the dimension of  $2.5 \times 2.5 \times 50 \text{ cm}^3$  and 476 crystals with the dimension of  $5 \times 5 \times 50 \text{ cm}^3$ . Those are undoped CsI crystals used at the Fermilab KTeV experiment.

We first measured the energy, timing, and position resolutions of a small calorimeter consisting of 144 2.5 cm square crystals with positrons. Figure 4 shows the obtained energy and timing resolutions[9]. We understood the performance from first principles. We then stacked crystals and built the calorimeter at J-PARC in 2010. The calorimeter was tested with cosmic ray muons,  $K_L \rightarrow \pi^0\pi^0\pi^0$  and  $K_L \rightarrow \pi e \nu$  decays. Figure 5 shows an event display of the calorimeter and invariant mass distribution of 6 photon events. We confirmed and established the calibration method of the calorimeter.

### 2.3. Veto detectors

Veto detectors surround the decay volume, as shown in Fig. 1, to detect the additional particles except two photons from  $\pi^0$  decays. Most of the veto detectors are upgraded.

One of the upgraded veto detectors is Charged Veto (CV). The CV is placed in front of the CsI calorimeter to detect charged particles hitting the calorimeter. It

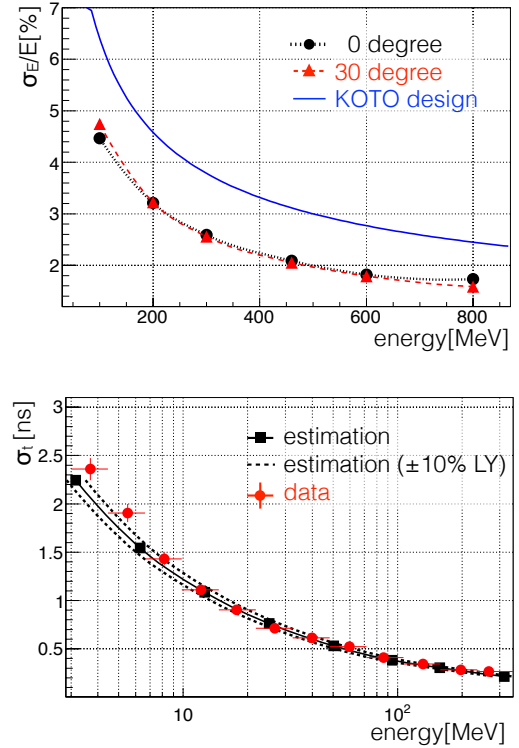


Figure 4: Observed energy and timing resolutions of the small calorimeter[9]. top) Energy resolutions for various energies and incident angles. The blue solid line shows the designed value of the KOTO experiment. bottom) Timing resolutions as a function of the deposit energy in a crystal. The black solid line with dots shows the estimated timing resolution and the red dots show the result obtained with data.

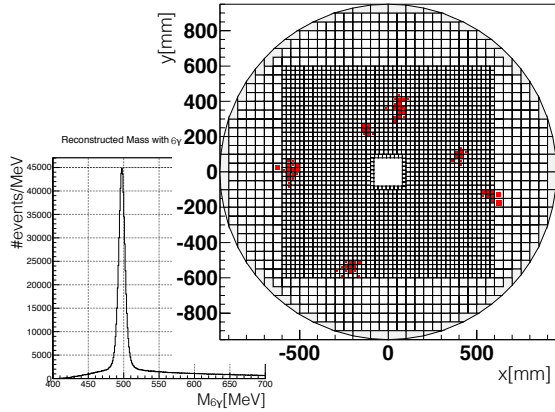


Figure 5: The invariant mass distribution of 6 photon events (left) and an event display of the CsI calorimeter (right). The size of the box in each crystal is proportional to the deposit energy in a crystal.

consists of two layers. One of them is placed on the upstream surface of the calorimeter, and the other is placed 25 cm upstream of the calorimeter. Each layer consists of thin (3 mm) plastic-scintillators to suppress neutron interactions. Signals from the scintillators are read by MPPC through WLS fibers. To achieve a small detection inefficiency, light yield is crucial. We built two layers of CV and measured the light yield of them at the  $K_L$  beam line. The measured light yields are large enough to ensure only small detection inefficiency.

Neutron Color Counter (NCC) is another upgraded detector. The NCC consists of 48 modules made of 3 CsI blocks glued together, and is placed at the entrance of the decay volume surrounding the  $K_L$  beam. The NCC is designed not only to detect photons from  $K_L$  decays, but also to measure the flux and energy spectrum of beam halo neutrons. All the NCC modules were constructed, and confirmed to have large enough light yields with cosmic ray test.

Beam Hole Photon Veto is also an upgraded detector. The BHPV is placed at the downstream end of our detector system to detect photons escaping from the decay volume through the beam hole in the calorimeter. The BHPV consists of 25 Cerenkov counter modules. Each module is composed of a lead plate, a stack of aerogel tiles, a mirror, a Winston cone, and a PMT. The lead plate converts photons to electrons and positrons, and the aerogel tiles emit Cerenkov light from the electrons and positrons. By using Cerenkov light, BHPV is not sensitive to heavy particles such as neutrons in the beam core. To suppress shower components going back to other veto counters, BHPV is placed inside a radiation shield.

Main Barrel (MB) surrounds the side of the decay volume. The MB consists of 32 modules, and each module consists of an existing module from the E391a experiment[10] and a new additional module. The E391a module is made of 45 layers of lead and plastic-scintillator sheets, and its total thickness is  $14 X_0$ . We plan to add  $5 X_0$  thick modules inside the existing modules. The designing of the additional modules is finished and a prototype module is being prepared. The  $K_L \rightarrow \pi^0 \pi^0$  background due to the detection inefficiency of the MB is the largest background of the KOTO experiment. By adding the new modules inside of the old ones, this background is reduced by a factor of 7.

#### 2.4. Waveform digitization and data acquisition

Signals from all the detectors are read out by Flash ADC (FADC) boards. At the beginning, signals from all the detectors are digitized by 14-bit 125 MHz FADCs with 10-pole Bessel filter. As the beam power increases, 125 MHz FADCs for some detectors, such as detectors in the beam core, will be replaced to 12-bit 500 MHz FADCs without the filter, to cope with the higher counting rate. The 125 MHz FADC boards were already manufactured, and operated for the calorimeter and veto detectors. For the 500 MHz FADC board, prototype boards were produced and tested. We are ready to manufacture the 500 MHz FADC boards.

Figure 6 shows an overview of the DAQ system. Digitized waveform data is stored in the boards temporally for 4  $\mu$ s. Each FADC board receives analog inputs, calculates the local sum of them and sends the sum to one of Level1(L1) trigger boards every 8 ns. A master control board of this DAQ system called MACTRIS communicates with the L1 trigger boards, generates L1 triggers based on those sums, and sends triggers to the FANOUT boards. The FANOUT boards fan-out the triggers and also clock signals to each FADC board. When a FADC board receives a trigger, the board sends corresponding waveform data to a so called Level2(L2) trigger board. The L2 trigger board has dual memories on it, and keeps storing data sent from the FADC boards during a spill after some event selections. The stored data is sent to an event building system during the next spill.

Reading out data through the above scheme was tested and established, with relatively simple L1 selection and no L2/L3 selections. We will keep developing and implementing more sophisticated selection algorithms in the trigger system.

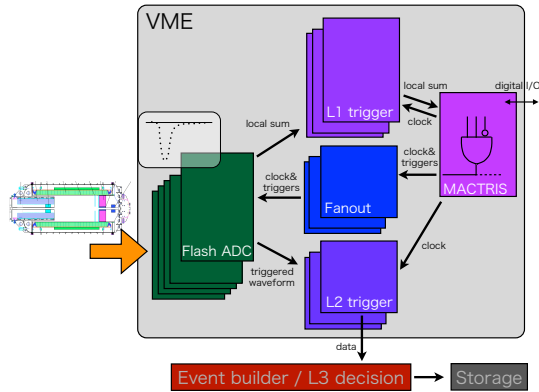


Figure 6: Overview of the DAQ system for KOTO experiment.

### 3. Summary and prospects

The KOTO experiment is the experiment to search for new physics by observing the  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay. The experimental apparatus is almost ready to take physics data, and the first physics run will start in the spring of 2013. The experimental sensitivity will cross the Grossman-Nir bound and new physics search will be started. After the first physics runs, a beam shut-down is planned for an upgrade of the linac. With the linac upgrade, we expect to have more beam power. The expected final sensitivity of KOTO experiment will reach the SM prediction, and KOTO will explore extensive parameter spaces of theories which give the branching ratio of  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  above the SM prediction.

### References

- [1] L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983).
- [2] J. Brod, M. Gorbahn, and E. Stamou, Phys. Rev. D **83**, 034030 (2011).
- [3] J. K. Ahn *et al.* (E391a Collaboration), Phys. Rev. D **81**, 072004 (2010).
- [4] H. Morii, Experimental Study of the Decay  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ , PhD thesis, Kyoto University, (2010).
- [5] Y. Grossman and Y. Nir, Phys. Lett. B **398**, 163 (1997).
- [6] A. V. Artamonov *et al.*, Phys. Rev. Lett. **101**, 191802 (2008).
- [7] G. Takahashi *et al.*, Jpn. J. Appl. Phys. **50**, 036701 (2011).
- [8] K. Shiomi *et al.*, Nucl. Instrum. Meth. A **664**, 264 (2012).
- [9] E. Iwai, CsI calorimeter for the J-PARC KOTO experiment, PhD thesis, Osaka University, (2012).
- [10] Y. Tajima *et al.*, Nucl. Instrum. Meth. A **592**, 261 (2008).