A new cylindrical photon-veto detector for the KOTO experiment

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Abstract. The KOTO experiment at the J-PARC laboratory seeks to obtain the first observation of the \( K_L \to \pi^0\nu\bar{\nu} \) decay. The branching ratio is calculated in the Standard Model (SM) to be \( 3 \times 10^{-11} \). This is a good probe to explore new physics beyond the SM with small theoretical uncertainty of \( \sim 2 \% \). We installed a new barrel-shaped photon veto detector, named the Inner Barrel, inside the KOTO detector to improve detection efficiency of photons from the major background of \( K_L \to 2\pi^0 \) decay. The Inner Barrel detector is a sampling calorimeter, consisting of 25 layers of 5-mm-thick scintillators and 24 layers of 1-mm-thick lead plates, corresponding to 5 radiation lengths. The volume is 3 m long along the beam direction, and inner and outer diameters are 1.5 m and 1.9 m, respectively. Scintillation light is read out by a photomultiplier at both ends via wavelength shifting fibers. The Inner Barrel was installed in April, 2016 and the performance was demonstrated at the beam time in June. In this paper, the detector design, construction and performance evaluated with the neutral beam are presented.

1. Introduction

The very rare kaon decay \( K^0_L \to \pi^0\nu\bar{\nu} \) is a sensitive probe for direct CP violation in the quark sector. The decay is a Flavor Changing Neutral Current process and is induced through electroweak loop diagrams. The branching ratio is predicted to be \( 3 \times 10^{-11} \) in the Standard Model [1], and the theoretical uncertainty is estimated to be only a few percent. The decay is also sensitive to new physics scenarios beyond the Standard Model such as Supersymmetric theories.

The latest experimental result was obtained from the E391a experiment at KEK 12 GeV PS, and the upper limit on the branching ratio was \( 2.6 \times 10^{-8} \) (90\% C.L.)[2]. The goal of the KOTO (K0 at TOkai) experiment is to study \( K^0_L \to \pi^0\nu\bar{\nu} \) at the Standard Model sensitivity [3].

2. An Inner Barrel detector

A schematic cross-sectional view of the KOTO detector is shown in Fig. 1. The KOTO detector subsystems are categorized into two parts. One is the CsI calorimeter, which detects two photons from \( \pi^0 \) decay, and the other is a set of hermetic veto counters, which demand no energy deposit in the \( K^0_L \to \pi^0\nu\bar{\nu} \) events.

One of the main backgrounds is the \( K^0_L \to 2\pi^0 \) decay, also shown in Fig. 1; two photons are undetected due to the inefficiency of the veto detectors. The Main Barrel (MB) detector which has large coverage in the transverse region, has only 13.5 \( X_0 \). A new detector, the Inner Barrel (IB), was motivated to decrease...
the inefficiency by adding 5 $X_0$ another inside the MB. According to the Monte-Carlo (MC)
estimation, the amount of $K_L^0 \rightarrow 2\pi^0$ will be suppressed by a factor of three.

The IB detector is a sampling calorimeter as shown in Fig. 2. It consists of 25 layers of
5-mm-thick scintillators and 24 layers of 1-mm-thick lead plates, corresponding to 5 $X_0$. The
32 modules were made in a trapezoidal shape and formed as a cylindrical detector. The volume
is 3 m long along the beam direction, and inner and outer diameters are 1.5 m and 1.9 m,
respectively. Scintillation light is read out by a photomultiplier (Hamamatsu R329-EGP or
R7724-100) at both ends via Wave Length Shifting (WLS) Fibers (BCF92).

3. Module production, construction and insertion to the existing KOTO detector
First, we attached WLS fibers to all 800 scintillators with UV adhesive. After the fibers were
 glued, we found some cracks in the scintillators caused by uncured adhesive behind fibers. We
reproduced new scintillators with fibers for those who have large cracks and also annealed to
other scintillators at 80°C for 3 hours to increase chemical resistance based on the result of
damage test.

In 2015, we started to make modules as shown in Fig. 3. To bundle the module, we used 0.75
mm-thick stainless band in 9 points. The accuracy of the module production was determined to
less than 1 mm. The modules were supported by 8 rings as shown in Fig. 4. All the production
and construction processes were made in KEK. The detector was delivered to J-PARC, and then
installed in April 2016. To insert the IB in the MB, the IB detector was pulled on the teflon
plates attached to the MB and the support rings.

4. Performance check
After installation, the performance of the IB detector was evaluated with the data. Figure
5 shows the timing resolution evaluated with cosmic-rays passing through the MB and IB
detectors. We obtained the timing resolutions by comparing relative hit timings between the
MB and the IB. The results were almost consistent with the expected values considering the
light yield, the decay time of WLS fibers and readout modules.

In May-June 2016, the first physics run with the IB detector was performed. To check the veto
response of the IB, we studied events which had four photons in the CsI calorimeter requiring no
energy deposit in the MB and the IB. As shown in Fig. 6, we can observe the 498 MeV/c² peak of $K_L \rightarrow 2\pi^0$ and background contribution mainly from $K_L \rightarrow 3\pi^0$. Background contribution of $K_L \rightarrow 3\pi^0$ estimated by MC is also plotted and it well reproduces the data.

**Figure 3.** Module construction.

**Figure 4.** IB support rings.

**Figure 5.** Timing resolution as function of module IDs evaluated with cosmic-rays for several IB (blue) modules. The timing resolutions of the MB inner (red) and outer (green) parts are also plotted.

**Figure 6.** Reconstructed $K_L$ mass using 4 photons in the CsI detector. Selection of no hits in the IB and MB detectors were applied. Black points show 2016 run data, and blue points show $K_L \rightarrow 3\pi^0$ MC.

5. Summary

We installed a new photon-veto detector to the KOTO experiment in April 2016. The IB detector is expected to suppress the main background from $K_L^0 \rightarrow 2\pi^0$ to be one third. The performances evaluated with the cosmic-ray and the neutral beam data are consistent with expectations and further study is on going.

References

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