Status and future prospects for the KOTO experiment

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The KOTO experiment at the J-PARC laboratory seeks to obtain the first observation of the $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ decay, as a direct measurement of the CP-violating parameter in the Standard Model. The almost full detector and the DAQ system have been completed and the KOTO experiment is ready to accumulate the first physics data is being prepared at May-June 2013. In this talk, expectation of the sensitivity at the first physics run and future prospects including a detector upgrade will be discussed.

2013 Kaon Physics International Conference,
29 April-1 May 2013
University of Michigan, Ann Arbor, Michigan - USA

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1. Introduction

The very rare 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 that is induced through electroweak loop diagrams. The branching ratio for $K^0_L \to \pi^0 \nu \bar{\nu}$ is predicted to be $2.4 \times 10^{-11}$ in the Standard Model, 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 derived from E391a experiment at KEK 12 GeV PS, and a branching ratio is estimated $2.6 \times 10^{-8}$ as an upper limit [1]. The goal of the KOTO (K0 at TOkai) experiment searches for $K^0_L \to \pi^0 \nu \bar{\nu}$ at the standard model sensitivity [2].

2. Experimental design

A schematic cross-sectional view of the KOTO detector is shown in Figure 1. The KOTO detector is categorized two sections. One is the CsI calorimeter which detect two photons from $\pi^0$ decay and other is a hermetic veto detectors which are required no energy deposition for $K^0_L \to \pi^0 \nu \bar{\nu}$ event.

A detector design is the same concept as those from the E391a experiment. In the E391a experiment, a limitation of single event sensitivity is estimated to be $1.1 \times 10^{-8}$ from so-called halo-neutron background [1]. The halo-neutron are distributed surrounding the beam and they hit the detectors around the beam hole. Then, this reaction can generate $\pi^0$ or $\eta$ and they will be the background for $\pi^0$ measurement. To suppress the halo-neutron background, we improved both the neutral beam and the detectors.

![Figure 1: A schematic cross-sectional view of the KOTO experiment](image)

2.1 The neutral beam

A plan view of the neutral beam line is shown in Figure 2. The 30 GeV/c proton beam is extracting from the J-PARC main ring and secondary particles are generated by hitting the target
made by Ni, Pt or Au. The KOTO beam line is selecting neutral particles which are generated 16 degree production angle. The remaining particles after the 20 m length collimator with the sweeping magnet are $K_L^0$s, neutrons and photons (neutral beam).

The halo-neutron are produced by multiple scattering of beam neutrons on the beam line materials. The beam collimator is designed so that the scattered neutron never scatters at downstream materials. This structure will reduce the halo component and a design of halo / beam core ratio is $10^{-5}$ [3]. We performed beam survey, and we got the expected beam profile and 2.6 times larger number of $K_L$ yield than that estimated in the proposal with Pt target [4, 5].

![Figure 2: A plan view of the neutral beam line](image)

2.2 Detectors

The paper only describes detectors in terms of the halo-neutron background. More details are written in [2, 6].

To reduce the halo-neutron background, we made major upgrades to the detectors which are placed around the beam hole. A NCC (Neutron Collar Counter) constructed by pure CsI crystal is placed upstream and its crystals are segmented along the beam direction to identify neutrons. The NCC can have self veto system of the halo-neutron background, and also has capability of halo-neutron measurement. A CV (Charge Veto) constructed by 3 mm thick scintillators is placed in front of the CsI calorimeter. This low material will suppress the halo-neutron background while keeping good efficiency for charged particles. We also upgraded the CsI calorimeter to be longer than those of the E391a experiment. The long crystal corresponds to 27 $X_0$ will improve the resolution of the reconstructed vertex of the $\pi^0$. These detectors are already installed and well functioning.
3. DAQ

A data flow of the KOTO DAQ is shown in Figure 3. Signals coming from the detectors are recorded as a waveform by 125 or 500 MHz pipeline ADC.

The events are selected by 3 levels of trigger logics. In the level 1 trigger, ADC values are summed up from all channels in each detectors. We can select the event by the energy deposition in the CsI calorimeter and also reject by the energy deposition in the veto detectors. In the level 2 trigger, we can calculate values related to the kinematics of $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$. Here, we employ a COE (Center Of Energy) defined as,

$$COE \equiv \sqrt{\left(\sum E_i x_i\right)^2 + \left(\sum E_i y_i\right)^2} / \sum E_i,$$

where $E_i$ and $x_i$ ($y_i$) are the energy deposition and the position of $i$-th CsI crystal, respectively. The COE value of $\pi^0$ of $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ must be large due to the energy balance taken by neutrinos. The level 3 trigger consists of the event reconstruction by the PC farm. We are currently preparing the clustering algorithm to reduce the data size.

With the current proton beam intensity, up to 24 kW during J-PARC run49, the event reduction using the level 1 and 2 looks enough to accumulate the data, but close to the limitations. In the near future we need upgrades of the level 1 and 2 triggers and to implement the level 3 trigger to reduce the data size.

4. Expectation of a sensitivity for the first physics run and the prospects

After constructing the detectors, engineering runs were performed on December 2012 and January 2013. The analysis is ongoing and some preliminary results are shown on the another paper presented at this conference [6]. We are currently checking all systems during a short physics run with the 15 kW proton beam intensity.
The beam will be back at May 13th and we will start to accumulate the physics data. To cross the Grossman-Nir limit, we estimated to require 35 days with 15 kW beam intensity. While we had an accelerator upgrade, we would have 33 days with 20 kW or more beam intensity. The first physics run sounds reasonable to cross the Grossman-Nir limit.

The proton beam intensity will be upgraded 50 kW at 2014 and 100 kW at 2015. If we are assuming that the data is accumulating 4 months in each year, the single event sensitivity will reach the standard model sensitivity in 2017.

5. Detector upgrade

After suppressing the halo-neutron background, the main background will be due to missing photon from $K_L^0 \rightarrow 2\pi^0$ due to the photon detection inefficiency. According to the simulation study, the signal level is comparable to the background level for the standard model sensitivity with the current KOTO setup. The main background event is missing photon at a MB (Main Barrel) detector. The MB is a largest component of the veto system and it consists of Pb+scintillator sampling calorimeter which has 14 $X_0$.

To reduce the background above, we are planning to add a same type of calorimeter, so-called Inner Barrel, inside the MB. The inner barrel will add 5 $X_0$ more and it will reduce the photon inefficiency caused by the penetration. With this upgrade, a signal to noise ratio is expected to be improved by a factor of 1.8.

Currently, we are testing a 30 cm-long prototype and evaluating the way to stack and support the detector. Also we are measuring the light yield of fibers and scintillators. We target the installation within 2013.

Figure 4: A schematic view of the Inner Barrel upgrade

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1The beam was terminated due to an accident.
6. KOTO step2

The goal of the KOTO experiment is achievement to search $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ with the standard model sensitivity (so-called KOTO-step 1). We are planning the KOTO-step 2 experiment to reach 100 events for the standard model sensitivity [2]. At the step 2, we need to gain the $K_L$ yield by,

- Higher intensity beam : 290 kW -> 435 kW ;
- Smaller extraction angle : 16 degree -> 5 degree ;
- Longer decay volume : 2 m -> 11 m.

A schematic view of the KOTO-step 2 is shown in Figure 5.

The possibility of the 5 degree extraction beam line is under discussion with a hadron hall extension (Figure 6). The plan is to extend the hadron hall and to install 2 more targets to allow more experiments to us simultaneously. The location of KOTO step 2 is behind the beam dump with the neutral beam extracted from the 3rd target. The beam line will be placed inside the beam dump.

![Figure 5: A schematic view of the beam line and detectors for KOTO step 2](image)

![Figure 6: A plan of the hadron hall extension at J-PARC. The design is currently being discussed in KEK. Current hadron hall is shown as blue dotted line](image)
7. Summary

The KOTO experiment at the J-PARC searches for $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$. All detectors and DAQ system are ready to accumulate the physics data. We are going to start the first physics run in this May and the data will cross the Grossman-Nir limit. The final sensitivity is expected to reach the standard model prediction with higher beam intensity and the detector upgrades. Furthermore, we are planning the KOTO-step 2 experiment and the goal of sensitivity is an order of $10^{-13}$. The long range plan is shown in Figure 7.

Figure 7: A plan for $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ measurement at the KOTO experiment.

References