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Kaon experiments at J-PARC

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Abstract

The newly constructed high-intensity proton synchrotron, J-PARC (**J**apan **P**roton **A**ccelerator **R**esearch **C**omplex), has completed its first stage of construction and started accelerator commissioning. Many experiments using slowly extracted proton beam are proposed and being prepared. Among them, two experiments to study Kaon decays, KOTO to search for a $K_L \rightarrow \pi^0 \nu\nu$ decay and TREK for violation of Time-Reversal invariance, are under preparation. In this article, current status of the experiments is reported.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

In these days, particle physics is being studied in three interrelated frontiers; the Energy Frontier, the Intensity Frontier and the Cosmic Frontier. With the intense particle beams, the properties of neutrinos will become clear and various rare processes will be observed, which will tell us about new physics beyond the Standard Model [1]. The J-PARC, newly constructed high-intensity proton accelerator facility in Japan [2], will be the best place to perform the intensity frontier researches.

The Hadron Experimental facility in J-PARC will provide high-intensity Kaon, pion and muon beams produced by slowly extracted proton beam to the experimental area. With these secondary particles, ~~variou~~s experiments are designed and being prepared for particle and nuclear physics studies [3]. Among them, two experiments by using Kaon decays, TREK and KOTO, will be introduced briefly and their status is given in this article.

2. J-PARC and Hadron Hall

The J-PARC will provide protons having the highest beam power as much as 1MW for wide research fields; particle and nuclear physics, material science, life science and nuclear transmutation. After finishing construction started in 2001, the J-PARC accelerators enter a commissioning stage and have succeeded in delivering proton beams to all experimental facilities already in 2009. Their commissioning is continuing for early realization of designed beam power.

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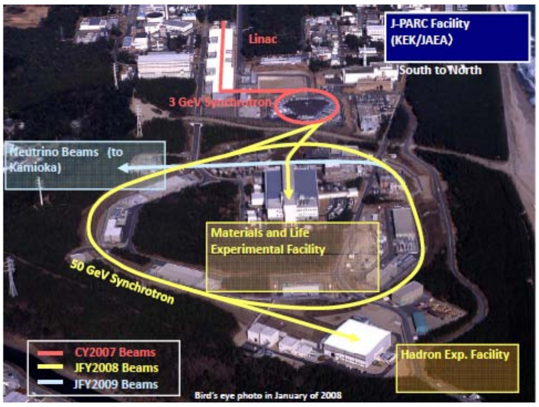

Fig. 1. Bird's eye photo of the J-PARC.

Figure 1 shows the J-PARC accelerator composed of Linac, 3 GeV synchrotron called as RSC (Rapid Cycle Synchrotron) and 50 GeV synchrotron called as MR(Main Ring). There is an experimental facility, MLF (Materials and Life Experimental Facility), using muons and neutrons produced by 3 GeV protons. Small portion of protons accelerated to 3 GeV enter to the MR and accelerated to the 50 GeV[1]. There are two experimental facilities, Neutrino Experiment Facility and Hadron Experiment Facility, for nuclear and particle physics.

Figure 2 shows a layout of the Hadron Experiment Facility in which the two Kaon experiments will be performed. The 30 GeV proton beam is extracted slowly during 0.7 second from the MR, and hit secondary production target (T1) made of 6-layers of Ni-disks. The generated secondary particles will be extracted to two charge (K1.8 and K1.1) and one neutral beam (KL) line at the same time. Also, each charged beam line has two experimental areas. As a result, five experiments will be prepared and three experiments be performed at the same time [2].

Fig. 2. Layout of the hadron experiment facility. TREK will be performed at K1.1BR/K0.8 beam line while KOTO will do at KL beam line.

3. TREK

The TREK [3] experiment aims at searching for violation of time reversal invariance by using $K^+ \rightarrow \pi^0 \mu^+ \nu$ ($K_{\mu 3}$) decay. The time reversal (T) invariance is a discrete symmetry which is one of basic concepts in particle physics together with charge conjugation (C) and parity reflection (P). The T-invariance implies that we can describe interactions between particles regardless a convention of time direction. Assuming the CPT theorem in quantum field theory, the T-violation is equivalent to the CP-violation.

A transverse muon polarization (P_T) in $K_{\mu 3}$ decays is a T-odd observable, and becomes a clear signature of T-Violation [4]. Since the contribution to the P_T from the standard model is negligibly small ($\sim 10^{-7}$), an observation of non-zero P_T will be connected to a new source of the CP-violation which is necessary to explain the baryon asymmetry in the universe.

3.1. TREK's strategy

Figure 3 shows current experimental limit given by E246 experiment [5] and expected sensitivity of the TREK with various theoretical expectations to the P_T. It is desirable to perform an experiment with its sensitivity to 10^{-5} by considering the range of predictions of existing models and the size of final state interaction effect. That is, there is wide window for new physics in the range.

In order to improve the sensitivity, we have to reduce in both of statistical and systematic errors. Since the statistical sensitivity in the asymmetry measurement improves proportional to the square root of the analyzed events, we need 100 times

[1] The facility is approved as a two-step project and has completed construction of its first phase. During the first phase, the MR will provide 30 GeV proton beam.

[2] Currently, K1.1 is not constructed, yet. There are several options on further secondary beam line construction.

[3] TREK is an acronym of Time Reversal Experiment with Kaons.

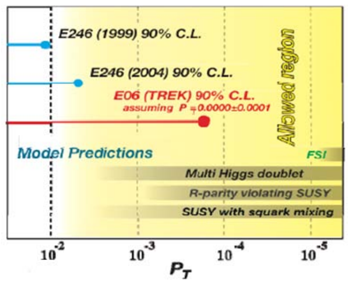

Fig. 3. Current experimental limits and TREK's goal.

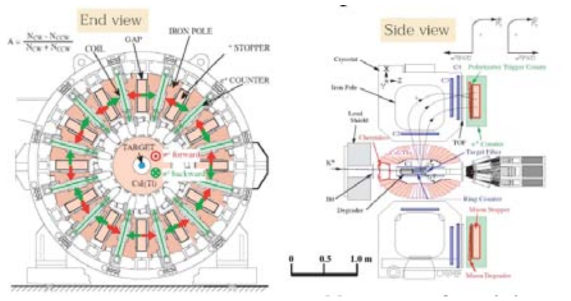

Fig. 4. The E246 experimental setup.

statistics for 10 times of improvement. That is, we need a facility to provide high intensity kaon beam and detector system having large acceptance. On the other hands, it is essential to proceed in a steady way to reduce systematic errors. We have to understand the sources of systematic error and invent the method to reduce them one by one.

The TREK will reach its sensitivity to 10^{-4} by using upgraded E246 experimental detectors at the J-PARC, which will improve current experimental sensitivity by factor of 20 in statistically and by 10 in systematically. After obtain confidence for further improvement, the experimental group will design and propose an experiment to achieve 10^{-5} sensitivity.

3.2. The E246 experiment

The most recent and highest precision experiment was performed at the KEK proton synchrotron [5]. The experiment used 660 MeV/c K^+ beam stopped at an active target made of scintillation fibers. As shown in Figure 4, the detector system consisted of (1) barrel-shape electromagnetic calorimeter made of CsI(Tl) crystals to reconstruct π^0, (2) tracking chambers and Toroidal superconducting magnets to determine momentum vector of muons and (3) polarimeters made of two plastic scintillation plates surrounding both sides of aluminum slabs (stopper) where muon stopped and decayed. Since the angular distribution of positrons produced at the muon decays depends on the direction of muon spin, P_T is determined by an asymmetry of positron yields obtained at two opposite scintillation counters.

The novel technique taken at the E246 is 12-fold rotational symmetry, which prevents any detector efficiency in polarimeter from producing spurious asymmetry. Also, the feature of stopped Kaon decay enables us to use forward-backward symmetry, which removes most sources of systematic errors. Since the direction of the P_T in the event that π^0 moves to beam direction (forward) is opposite in the event that π^0 does to opposite direction to the beam (backward), spurious asymmetry is further removed by comparing two data sets according to π^0 direction, separately. The final result was

$$P_T = -0.0017 \pm 0.0023(\mathrm{stat}) \pm 0.0011(\mathrm{syst})$$

corresponding to the upper limit of $|PT| < 0.0050$ (90% CL).

3.3. From the E246 to the TREK

The E246 result improved an effective suppression of systematic errors with a rotational and a forward-backward symmetry. The remained largest error was caused by multiple scattering[4] in front of polarimeter, which will be removed at TREK by an upgrade of the polarimeter. This new polarimeter consists of alternating stopper plates and drift chambers, which enables us to detect positron close to where muon stops and decays. Compared to the E246 polarimeter in which the scintillators were located far from the muon stopping position, the new active polarimeter has 10 times larger detection acceptance and free from the multiple scattering effect.

Tracking system will be improved in order to reject in-flight decay of π^+ produced at the $K^+ \rightarrow \pi^0\pi^+$ decays, which was a source of considerable size of systematic error. Also, a uniform magnetic field to hold muon spin at the polarimeter will be prepared.

[4] Due to the multiple scattering after tracking system makes an distortion on stopping distribution at the polarimeter, which induce a change of acceptance of positron counting.

Finally, the photo-sensors of CsI(Tl) calorimeter will be replaced to the avalanche photo-diodes to fit high-rate environment.

The K1.1BR/K0.8 beam line will be constructed on September, and its commissioning is planned during beam time started on October, 2010. The Toroidal spectrometer will be installed in the experimental area in 2011 and other detector components will be installed gradually. Since the P_T measurement needs designed (high) beam intensity, the experimental group will construct and study detector system by performing other measurements requiring relatively lower beam intensity such as a test for lepton universality in kaon decays [6].

4. KOTO

The KOTO[5] experiment aims at searching for a $K_L \rightarrow \pi^0 \nu\nu$ decay. The $K_L \rightarrow \pi^0 \nu\nu$ decay is a direct CP violation process caused by a flavor changing neutral current (FCNC) resulting in a transition from strange to down quarks. The most attractive feature of the decay is that its branching ratio can be calculated with very small theoretical uncertainties. Without any ambiguities due to low energy processes, it will test the Standard Model most seriously and clarify any new physics effect if there is. During the last decade, theoretical studies on the decay showed remarkable achievement and a lot of expectations based on various new physics scenarios [7].

The key question related to the $K_L \rightarrow \pi^0 \nu\nu$ decay is how to measure its branching ratio experimentally. Since the Standard Model expects its branching ratio as 2.5×10^{-11}, we should examine huge number of KL decays to observe the event. That is, we need a high-intensity beam line and a dedicated detector system to remove background events caused by the large number of KL decays. In addition, there are only limited constraints to identify the decay because it is three-body decay including two neutrinos.

KOTO will use the detection method established at the KEK-PS E391a experiment [8], which is expressed as '*pencil beam + hermetic veto*'. Among three decay products in the $K_L \rightarrow \pi^0 \nu\nu$ decay, only single π^0 is an object to be detected. Since the most of π^0 decay into two photons immediately, two-photon final state will be a candidate of the signal. In order to reconstruct π^0 form information of two photons, we need an assumption that π^0 decays at beam axis which is provided by the pencil beam.

The hermetic veto is necessary to ensure that the reconstructed π^0 is produced by the signal event. Only $K_L \rightarrow \pi^0 \nu\nu$ and $K_L \rightarrow \gamma\gamma$ decays have two-photon final state and are distinguished by other decay modes with a condition that there is no any accompanying particles except for two photons. The $K_L \rightarrow \gamma\gamma$ decay is easily removed by applying two-body kinematics.

4.1. KOTO's strategy

The goal of KOTO is to search for the $K_L \rightarrow \pi^0 \nu\nu$ decay with O(-11) sensitivity for the first observation with updated E391a detector and high-intensity KL beam at J-PARC. The E391a results indicated that the main background source is a halo neutron interaction. When a neutron apart from beam center (halo neutron) enters detector, a single π^0 is produced as a result of strong interaction between neutron and detector materials. Thus, KOTO is designed to reduce the halo neutron events three orders of magnitudes by the new beam line and detector upgrades.

Because there are many new physics scenarios to give larger branching ratio than that of the Standard Model, KOTO will examine the models with improving its sensitivity. After an observation of the decay, the experiment will move to precise measurement of its branching ratio by collecting more than 100 events.

4.2. Beam line

Figure 5 shows a schematic drawing of KL beam line for KOTO experiment. The KL beam line is extracted at 16^o with respected to the primary proton beam. The neutral beam is collimated by using two stages of long collimators made of iron and tungsten blocks. The collimation lines are designed to reduce multiple scattering of neutrons which is main source of halo neutrons. Also, the collimators are located inside vacuum in order to remove scattering with air

[5] KOTO is an acronym of K0 at Tokai viliage where the J-PARC is located.

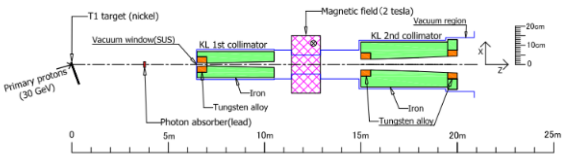

Fig. 5. Schematic drawings of KOTO beam line.

inside the beam line and will be connected directly to the vacuum chamber containing detectors. Charged particles inside the beam line are removed dipole magnet located between two collimators. In front of the first collimator, there is a photon absorber to reduce photon flux in order to reduce counting rate of detector locate on the beam hole.

Figure 6 shows profiles of neutrons given by a beam line simulation. Because the effective image of the T1 target shows rectangular from the detector, the collimation lines are optimized separately in vertical and horizontal plane for maximum in KL yield and minimum in halo neutron flux.

The KL beam line was completed on September, 2009 and a survey experiment was succeeded by February, 2010. The primary goal of the survey is to measure the KL yield because there was factor of three discrepancies among the simulation codes. Since the KOTO sensitivity is conservatively estimated based on GEANT4 calculation because it expected the smallest yield, the survey results is compared with the GEANT4 calculation as shown in Figure 7. The obtained KL momentum distribution shows slightly harder and the yield is larger by a factor of 1.3 than the expectations. The beam profile was obtained from counting rates of PWO crystal moving inside beam. The results agree quite well to those of the Monte Carlo simulation after including detector components.

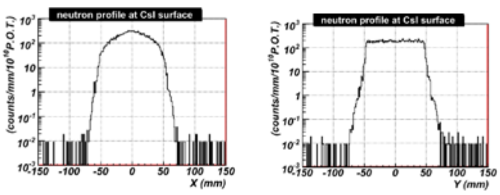

Fig. 6. Expected beam profiles of neutron in horizontal(Left) and vertical(Right). Halo neutrons are suppressed successfully down to 10^{-4}.

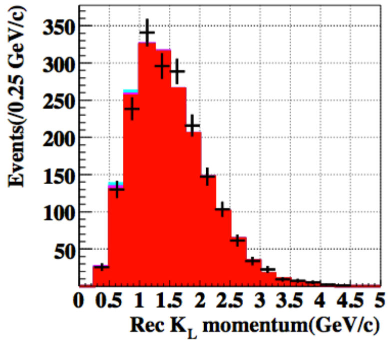

Fig. 7. Comparison of KL momentum distribution between data(dots) and GEANT4 expectation after applying a feed-back to the M.C. data.

4.3. Detector Preparation

A schematic view of KOTO detector system is given in Figure 8, of which configuration is same as that of the E391a and many parts of detector will be reused. There are, however, many upgrades at KOTO in order to reject neutron backgrounds and data taking under high-intensity environment.

The first item of upgrade is replacement of CsI crystals for the electromagnetic calorimeter. The new crystals which were used in the Ferimlab KTeV experiment are of two sizes, $2.5\times2.5\times50$ cm^3 for the central region (2240 blocks), and $5.0\times5.0\times50$ cm^3 for the outer region (336 blocks) those are longer and have smaller cross-section compared to the E391a crystals of size $7\times7\times30$ cm^3.

The 50 cm length (~ 27 radiation length (Xo)) of new crystals will make background events caused by the punch-through[6] negligibly small. Also, the long calorimeter contains the generated electromagnetic shower completely which prevent the reconstructed vertices from smearing into the signal region[7].

[6] Punch-through is a reason of photon detection inefficiency which is a phenomenon that photon passes through the detector without any interaction. Its probability decreases exponentially according to the length of detector.

[7] This is an important tool to suppress neutron related background observed at the E391a experiment. When part of electromagnetic shower escape detector, energy of photon is underestimated. As a result, the event is misidentified as a signal, even though the (real) generated position is the detector location far from the signal region.

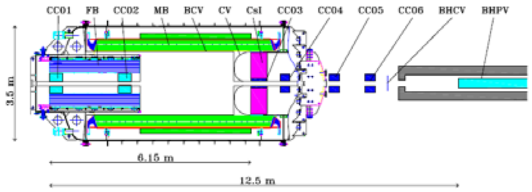

Figure 8. Schematic view of KOTO detector.

The smaller cross-section enables us to do *shower-shape analysis.* Since the shape of shower produced by neutron is different from that by photon, we can remove neutron induced events with the shower-shape. When two photons enter calorimeter closely and generated showers overlap, it is counted as a single photon. It means that we miss one photon completely and the event has large possibility to be background.

The signal of calorimeter is recorded by waveform digitizer in order to fit high-rate condition. An analog pulse of each channel is amplified and passed through a 10-pole filter/shaper which converts the fast pulse into a Gaussian shape keeping the total energy information constant. An incident energy and time of photon will be obtained by fitting of the output signal with a fixed-width Gaussian function. If there is a pile-up signals from legitimate two-photon signals, its shape will be different from the Gaussian.

The second one is Beam Hole Photon Veto (PHPV) which detects extra photons in the KL decay escaping through the beam hole. Since beam pass through the counter, the counter should be insensitive to beam particles with high detection efficiency to the photons. The BHPV is designed to be an array of lead-aerogel counters. Incident photon generates electro-magnetic shower at the lead plate and the shower particles do Cerenkov radiation. On the other hand, most of (heavy and slow) products in neutron interactions do not generate the Cerenkov radiation. In addition, the showers produced by photon develop along the beam direction while neutron-induced shower tends to go isotropic. With 25 layer of modules, we can analyze shower shape in the BHPV and reduce neutron signals without loss of photon-detection efficiency.

Finally, the barrel veto counter surrounding decay volume (MB in Fig. 8) will be reinforced. By adding additional 5 radiation length, it will be negligible the photon-detection inefficiency due to punch-through.

It is expected to complete the construction of electromagnetic calorimeter with full read-out system in 2010. An engineering run with the new calorimeter will be performed just after the construction.

KOTO detector system will be completed within 2011 and the first physics run will be performed by the summer 2012. Since the beam intensity used at the hadron hall is expected to be 10% of designed value at that time, KOTO sensitivity will be 1×10^{-9} with one month data taking, which is better than an indirect experimental limit called Grossman-Nir limits (1.2×10^{-9}) .

5. Summary

J-PARC provides high-intensity proton beams for nuclear and particle physics. There are two experiments using Kaon decays, TREK and KOTO. TREK will search for a T-Violation phenomenon by measuring non-zero transverse spin components of muon generated by the $K_{\mu3}$ decays with sensitivity 10^{-4}. KOTO will search for $K_L\rightarrow\pi^0\nu\nu$ decay with sensitivity better than standard model expectation aiming at the first observation of the decay. KOTO will complete the detector construction by 2011 and perform its first data taking by summer, 2012. Both of the experiments will keep improving experimental methods and equipments for their final goals with increasing of beam intensity at the J-PARC.

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