The KOTO Experiment at J-PARC

I. Overview

CP violation continues to be one of the compelling issues in particle physics. Several processes in K and B physics can provide incisive information about CP violation in quark flavor physics. Among them are the rare decays $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$, which have small theoretical ambiguities in the Standard Model (SM) and also in many extensions of the SM. Processes in B physics include asymmetries in the $B^0 \to J/\psi\, K_S^0$ decays and the ratio of B_s to B_d mixing.

The predicted branching ratios in the Standard Model for the two kaon decay modes are

$$\begin{array}{rll} K^+ : & (7.81 \pm 0.75 \pm 0.29) \times 10^{-11} & \text{[BGS11]} \\ K_L^0 : & (2.43 \pm 0.39 \pm 0.06) \times 10^{-11} & \text{[BGS11]}\,. \end{array} \tag{1}$$

Although the theoretical *precision* is very high, the *accuracy* given by the quoted errors (see Ref. [BGS11]) reflects uncertainties in the underlying SM parameters. Other experiments, including those in the B sector and with the CERN LHC, will help to reduce the overall errors to a few percent. Opportunities for critical tests of the SM are thus very high.

The experimental branching ratios for the two modes are

$$\begin{array}{llcll} \text{Expt.} & \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) & = & (1.73^{+1.15}_{-1.05}) \times 10^{-10} & \text{[Ad04,An04,Ad08,Ar09]} \\ \text{Expt.} & \mathcal{B}(K_L^0 \to \pi^0 \nu\bar{\nu}) & < & 2.6 \times 10^{-8} & \text{[Ahn10]}\,. \end{array} \tag{2}$$

The K^+ value is based on seven events in the BNL E787/E949 experiments, while the upper limit for the K_L^0 mode was recently established at the 90% confidence level in the E391a experiment at the KEK 12-GeV Proton Synchrotron in Japan [Ahn10].

From isospin relations, the K^+ decay rate sets an upper limit to the K_L^0 rate: $\mathcal{B}(K_L^0 \to \pi^0 \nu\bar{\nu}) < 4.4 \times \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ [GN97]. While the K^+ rate is consistent with the SM within errors, the K_L^0 rate is a factor of 15–90 above the corresponding Grossman-Nir (GN) limit.

An immediate goal for the KOTO experiment is to break through a critical threshold for possible 'New Physics' (NP): the Grossman-Nir limit.

The detector used for the E391a experiment at KEK [Ahn10] is being modified for much higher sensitivity. The experiment will be done in two steps. The goal of Step 1 is to make the first observation of the decay, and obtain about 3.5 SM events with 1.8×10^{21} protons on target and a signal-to-noise ratio of 1.4. In Step 2, the beam line and the detector will be upgraded and the expectation is to obtain more than 100 SM events with a S/N ratio of 5. The sensitivity goal for the branching ratio is 10^{-13} in Step 2.

II. Theoretical Motivation

The physics of the kaon rare decays has been described in detail in many places (see *e.g.*, Refs. [KN10,LV10,Li89,Bu94,BUS08]) and does not need to be elaborated here. The importance of these decay modes is well expressed in a recent review titled *"Waiting for precise measurements of $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$"* [BUS08].

The $s \to d$ transition is provided by loop and penguin diagrams. The K_L^0 decay is entirely dominated by direct CP violation. The branching ratio (BR) for the K_L^0 decay mode is proportional to the square of the quantity η, which governs CP violation in the common description of the CKM matrix. Other contributions are very small, as are also theoretical uncertainties.

Considering the precision with which the K-decay branching ratios can be computed, and their importance for critical SM tests, experiments dedicated to their measurement are compelling. Ideas Beyond the Standard Model (BSM) that can lead to large deviations from the SM include the MSSM model [Is06], 4-generation models [Ha99,Bu10], the Littlest Higgs Model with T-Parity [Go09,Bl10], lepto-quark exchange [GN97], and many others (see Ref. [BUS08] for discussion and references).

Confirmation of the SM predictions would lead to rejection of several models. On the other hand, new and exciting physics Beyond the Standard Model is open to discovery at the 5σ level between the Grossman-Nir limit [GN97] and the SM prediction [Br06]. Decay rates well below the SM prediction are also a discovery region.

III. Measurement of $K_L^0 \to \pi^0 \nu \bar{\nu}$ at J-PARC

The KOTO experiment has been fully approved at the J-PARC laboratory in Japan and is actively being installed.

III.A Requirements for the Experiment

The necessary requirements for and design of the experiment are well described in the full paper on the pilot E391a experiment [Ahn10]. The signal for the $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay is detection of exactly two photons with an invariant mass of a π^0, and nothing else. In short, the goal can be achieved through kinematic constraints, a detector as fully hermetic as possible, thorough knowledge of component detector efficiencies, and identification of all possible backgrounds.

Important decay modes include $K_L^0 \to \pi^0 \pi^0$ with a $\sim$0.1% branching ratio, $K_L^0 \to 3\pi$ (including $3\pi^0$ and $\pi^+\pi^-\pi^0$), $K_L^0 \to \gamma\gamma$, and $K_{\ell 3(\gamma)}$ decays. They provide backgrounds that can simulate the signal of interest by many orders of magnitude. Charged particles can generate signals that mimic photons or, if present at the same time of a good event, lead to vetoing the signal of interest. Serious backgrounds can also be produced from other particles such as neutrons from the production target and beam line.

III.B. Design of the Experiment

The K_L^0's are produced by a 30-GeV proton beam on a rotating, water-cooled stack of nickel disks. The beam will have an intensity of about 2×10^{14} protons per 0.7-s spill, with a repetition rate of 3.3 s. Secondary particles will be extracted at 16° into a beam line that extends 21 meters to the KOTO detector. A yield equivalent to about 18×10^6 K_L^0's per spill has been measured in a test run with an average momentum of about 2 GeV/c. There will also be $\sim 3 \times 10^8$ neutrons ($p_n > 0.78$ GeV/c) per spill. Compared to the E391a experiment with a 12-GeV proton beam and production angle of 4°, the K_L^0 rate is higher by about a factor of $\sim$40, and the n/K_L rate is expected to be reduced by about a factor of 3-4.

A 'pencil beam' [Wa05,Sh10] is very important to provide strong kinematic constraints on the analysis of the data. In addition to excluding backgrounds from other neutral decays, accidental backgrounds from halo neutrons or other particles must be suppressed to high order. A well-collimated neutral beam line was designed and constructed according to extensive Monte Carlo simulations. The fraction of $K_L^0/n/\gamma$ within ± 5 cm square at the end of the beam line is 99.99/99.80/99.82%, and only slightly less 615-cm downstream inside the hole through the CsI crystals. The measured K_L^0 beam rate is within 10% of the simulations with Fluka.

A schematic of the KOTO detector is shown in Fig. 1. It provides for (1) high acceptance, with a small hole down its center to let neutral particles pass through; (2) hermetic photon veto counters that have low detection inefficiencies around the decay region; and (3) high vacuum to minimize dead material in front of the main crystals. Together with the pencil beam, events that have only two photons must reconstruct to a π^0 that has a large pair transverse momentum. The CC collar counters as well as the CV, Main Barrel, and beam-hole components are being redesigned from the E391a detector for better performance.

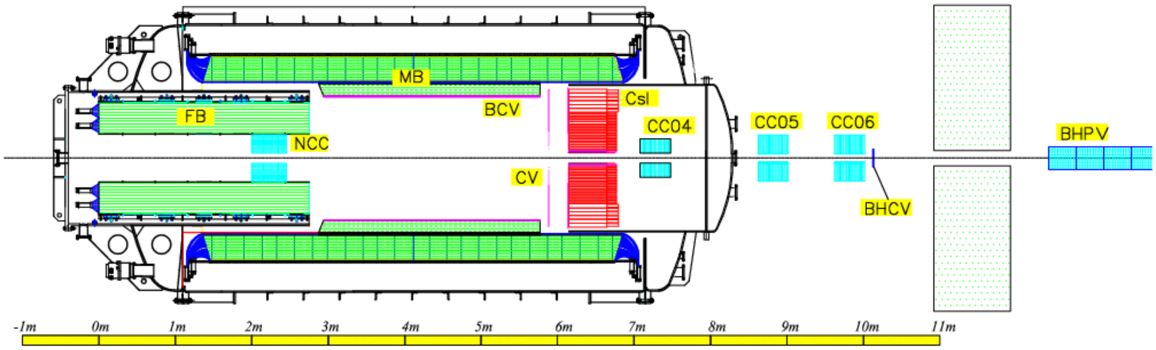

Figure 1: Schematic drawing of the detector. The components of the detector include collar counters (CCxx), Neutron Collar Counter (NCC), Front Barrel (FB), Main Barrel (MB), charged-particle vetos (BCV and CV), CsI crystals (CSI), Beam Halo Charged Veto (BHCV) and Photon Veto (BHPV).

III.C. Calorimeter Upgrade

The most critical feature in the detector is the performance of the main crystals. They must provide sufficiently precise information on the position of the clusters and angle information on the direction of the photons. To meet these needs, the 576 undoped CsI crystals (16 X_0) used in the E391a experiment have been replaced with 2240 crystals (27 X_0) 2.5-cm square and 476 crystals 5.0-cm square of undoped CsI used in the KTeV experiment at Fermilab. The phototubes from KTeV are also being reused.

III.D. Electronics

A unique data acquisition system is being developed for the experiment. The requirements for the CsI calorimeter include: (1) a pipeline system with no deadtime; (2) a 14-bit full energy range and 10-bit precision for charge measurement; and (3) time resolution better than 1 ns.

An innovative feature of the system is that the signals from the CsI phototubes will be passed through specially-designed 10-pole low-pass filters and then waveform digitized into 14 bits with a 125-MHz clock. The filter converts the pulse into a fixed and stable shape that is very nearly Gaussian with a FWHM of about 45 ns. The shape can be fit to obtain precise values for both charge (energy) and time. In addition, deviations or skews are possible signs of overlapping photon clusters, or other effects. The time resolution is better than 0.5 ns for energies greater than 10 MeV; it increases to $\sim$2 ns at 1-MeV energy due to photostatistics. The scheme makes separate ADC and TDC units unnecessary. The ADC boards have been built and thoroughly tested. Additional 500-MHz boards are being built for some of the veto detectors.

The system also has trigger boards at two levels. Each ADC board will provide, for each 8-ns time step, an energy sum of all input signals through a 2.5-Gbps transceiver and fiber optics cable to a level-1 (L1) board. A full crate of L1 boards will receive the summed energies from all ADC boards, and sum them through a VME back-plane daisy chain for input to a Master Control and Trigger Supervisor (MACTRIS). This unit provides the master clock for synchronization of the system, and other control functions. If the full energy sum exceeds a 300-MeV threshold for an event of interest, the MACTRIS will send a trigger signal to each ADC board. The signal is timed to coincide with the event of interest just before it leaves the pipeline. The data are transferred through a second 2.5-Gbps transceiver fiber optics cable to a level-2 (L2) trigger board. The L2 boards may impose additional requirements on the event, and transfer them between spills to a PC computer farm for event building and processing. The functions of the ADC and trigger boards are provided by programmed FPGA modules.

IV. Some Challenges

The KOTO experiment presents huge challenges, for at least two main reasons. First, in terms of physics, the SM branching ratio is exceptionally small, and it can be deeply buried under the backgrounds from other decay modes. Second, in terms of measurement, reaching to or below the level of the SM branching ratio in reasonable running time requires a beam of high intensity, and the detector system must be capable of handling the very large hit and event rates. Dealing with both of these issues requires careful planning and attention to all possible ways in which the signal can be obscured or mis-identified.

Based on estimates from Monte Carlo simulations, hit rates of particles in the CsI crystals from a K_L^0 beam file at the entrance of the detector are $>$2 million per spill at the design proton current on the production target. After applying vetos from charged-particle and the main barrel photon detectors, and also a 300-MeV total energy cut, the triggered event rate is estimated to be $<$100,000 per spill. The hit rate in the CsI crystals from neutrons and photons from the small fractions outside the beam core are $\sim$300,000 per spill, dominantely at very low energies. None of these particles will trigger events. Development continues to ensure that the DAQ system can handle these event rates. A current limitation is that, with little storage capability at the J-PARC site, permanent storage must be done over 1-Gbit lines to KEK. Methods may need to be developed for locally extracting only the essential information from the 8-ns digitized data, while ensuring that the signal criterion stated in Sec. III.A is not compromised.

The E391a experiment has demonstrated the viability of the method of the experiment, and provided excelllent experience in the many issues that must be handled. A factor of 1000 below the upper limit established by E391a for the $K_L^0 \to \pi^0 \nu \bar{\nu}$ decay must be achieved to reach the Standard Model prediction. This factor will come from the much higher K_L^0 flux, improved collimation of the beam, substantially reduced n/K_L^0 ratio, longer CsI crystals with smaller dimensions to improve granularity and event reconstruction, replacements of several veto detectors with improved designs and operations, and a unique, high-rate DAQ system. A factor of 20-100 needed to explore the interesting region below the Grossman-Nir upper limit should be achieved easily and quickly. Further development of techniques learned from these data should be able to provide the additional factor of 10.

V. Status and Schedule

After completing extensive Monte Carlo studies of the design for the neutral beam line in the J-PARC Hadron Hall, installation of the 20-m-long beam line including almost 14 meters of tight collimation was done during 2009. Monte Carlo simulations of the installed beam line have continued with production of event files for K_L^0s, neutrons, and photons at the end of the beam line (and entrance to the KOTO detector). Measurements of the K_L^0 flux were made in early 2010, and a paper has been submitted for publication.

Also in early 2010, a test run of an array of CsI crystals and development versions of the DAQ electronics was made with a positron beam at the Sendai laboratory in Japan. In October and November, additional engineering runs were made at J-PARC to examine the alignment of the beam line, study the calorimeter, and explore the neutron flux. Some data for $K_L^0 \to 3\pi^0$ were obtained to help develop data analysis techniques.

A more thorough engineering run was being prepared for April, 2011, then a large earthquake hit Japan in March. The laboratory was spared from the subsequent tsunami, but the earthquake did considerable damage, the most significant being the loss of alignments through the accelerator complex. Damages to the on-site KOTO apparatus were minimal. The beam will be restored over the next few months, and the KOTO Collaboration is preparing for an engineering run in the Spring, 2012. The electronics system will be completed, including provisions for veto detectors. Modifications are also being made to the CsI phototube bases to correct some problems due to vacuums.

An annual shutdown of the accelerator is scheduled for the Summer of 2012. At that time, the temporary setup of the KOTO detector components, outside of the vacuum tank, will be reassembled. The vacuum tank will be installed along with the new detector components (*e.g.*, CV, NCC) that are currently being constructed. An engineering run for the full system is estimated to start in late 2012, and will evolve into the first physics runs. It seems realistic that enough data can be obtained at this stage to break through the upper bound of the Grossman-Nir limits. The laboratory is planning a long shutdown in the Summer of 2013 for accelerator upgrades, after which long production runs will be done.

Assuming continued development of the primary proton beam, KOTO will steadily push the Grossman-Nir limit down with the goal of reaching the level of the Standard Model by ∼2017. Planning efforts for the major changes needed for Step2 have begun.

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