STATUS OF E391A – SEARCH FOR $K_L \rightarrow \pi^o\nu\nu$ DECAY

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The rare kaon decay, $K_L \rightarrow \pi^o\nu\nu$, is considered as an ideal process for understanding the origin of CP violation and a critical test for the standard model. The KEK-PS E391a is the first dedicated experiment to search for the decay. It employs two main concepts – *a pencil beam and a hermetic photon veto system in a highly evacuated decay region*. The experiment started data taking in February 2004 aiming at improving the current experimental limit by three orders of magnitude. The E391a is a pilot experiment for higher sensitivity at the new 50-GeV proton synchrotron in Japan (J-PARC) currently under construction. Using feedback from the E391a, an experiment with a sensitivity better than 10^{-13}, in which we expect to observe more than 100 events based on the standard model expectation, will be performed. In this report, the experimental principles and current status of data analysis are presented.

1. Introduction

Recent productive results of B-factories open a new era of the CP-violation studies, which need precise measurement of various parameters. In order to make a conclusive picture of the CP-violation and point out a signature of new physics beyond the standard model, it is required to study relationship among various processes with a high accuracy. One of the most attractive methods is to compare unitarity triangles deduced from two different systems, Kaons and B-mesons [1].

Especially, the $K_L \rightarrow \pi^o\nu\nu$ decay is the most attractive because the process is very clean in the theoretical calculation. The hadronic matrix elements can be extracted from $K^+ \rightarrow \pi^o e^+\nu$ decay. Concerning the short-distance QCD correction, the next-to-leading order calculation reduces the theoretical uncertainty to 1% [2]. The branching ratio of $K_L \rightarrow \pi^o\nu\nu$ decay is proportional to square of Wolfenstein parameter of the CKM matrix, η, which is a height of unitarity triangle in the ρ-η plane. Consequently, the measurement becomes the cleanest determination of the η. With the measurement of branching ratios for both $K_L \rightarrow \pi^o\nu\nu$ and $K^+ \rightarrow \pi^+\nu\nu$ decays, we can reconstruct the unitarity triangle in the K-decays with comparable accuracy to that in the B-decays even in the LHC-B [3].

A main question about the $K_L \rightarrow \pi^o\nu\nu$ decay would be "Is it really possible to be measured?". There are many difficulties in real measurement. Since it is a very suppressed process by the GIM mechanism, we need huge amounts of Kaon decays. In addition, the decay has very limited kinematical constraints to suppress the backgrounds because it is a three-body decay including two neutrinos.

The present experimental upper-limit is 5.9×10^{-7} [4], which is still far from the standard model prediction, 3×10^{-11}. It is quite challenging to improve sensitivity to determine the branching ratio with a few % errors. In order to reach the final goal, we take a step-by-step approach. As shown in Figure 1, the E391a is planned to improve current experimental sensitivity by more than 3 orders of magnitude. It is

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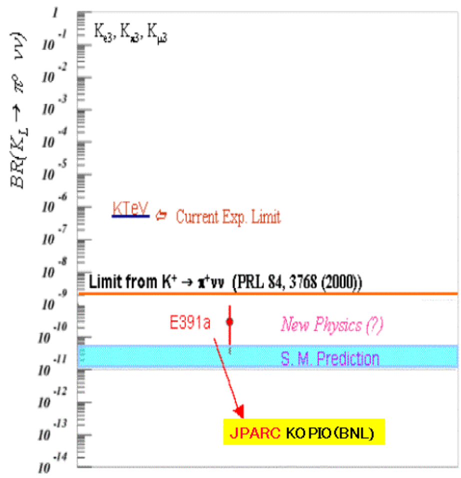

Figure 1. Current and future of the experiment for the $K_L \to \pi^o\nu\nu$ decay. The E391a is the first dedicated experiment for the decay and will become a guide to higher-sensitivity experiments in future.

a primary goal to cross an indirect limit, the Grossman-Nir limit, deduced from the branching fraction of the $K^+ \to \pi^+\nu\nu$ decay [5]. An experiment with a sensitivity better than 10^{-13} will be continued in the near future at the new high intensity proton synchrotron under construction, J-PARC [6].

2. Detection Principle

The event of $K_L \to \pi^o\nu\nu$ decay is defined as a clear single π^o without any accompanying particles. If you scan the full list of K_L decays, you may agree that the definition is quite persuadable. In the E391a experiment, the single π^o will be reconstructed by two gammas ($\pi^o \to \gamma\gamma$) which has two orders of larger branching fraction than that of the Dalitz decays ($\pi^o \to e^+e^-\gamma$) used at the previous experiment. It enables us to reach higher experimental sensitivity with the same number of K_L decays. It is expected, however, to increase background due to fewer kinematical constraints.

As shown in Figure 2, the detector system is cylindrically assembled with respect to the beam axis, consisting of barrel sampling calorimeters made of alternating lead and scintillating plates, electromagnetic (EM) calorimeter of undoped CsI crystals and a series of beam counters. The vertex of π^o is reconstructed from two gammas by their energies and positions measured at the EM calorimeter with a constraint of π^o-mass. From the reconstructed vertex, transverse momentum of the π^o with respect to the beam axis (P_T) is obtained, which will be used for selection of the signal.

The $K_{\pi 2}$ ($K_L \to \pi^o\pi^o$) decays are considered as a main background source when one of the π^o's is not detected due to inefficiency of the detector system. Since the branching ratio of the decay is 10^{-3}, we need an inefficiency level of 10^{-8} for π^o detection that corresponds to 10^{-4} for γ to suppress the background level down to the sensitivity of the standard model expectation. In order to achieve the high detection efficiency, a detector setup was carefully designed not to have any dead space surrounding the decay volume. Also, it was important to reduce electronic noise and increase the number of photoelectrons for a given energy deposit in the detector, which

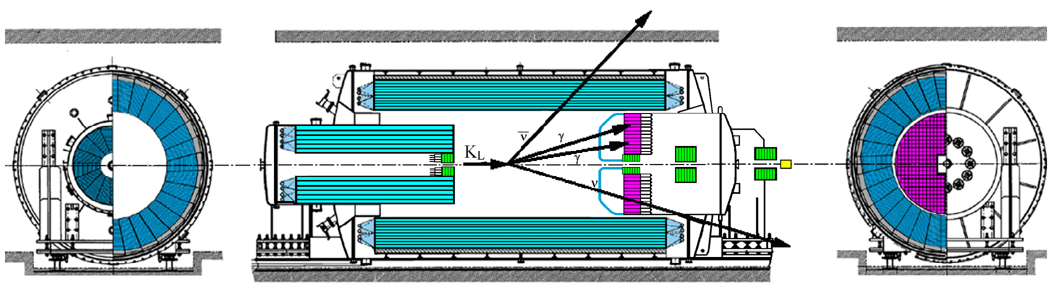

Figure 2. Schematic view of the E391a detector setup. Single π^o is reconstructed by detecting two gammas at the electromagnetic calorimeter and a hermetic veto system fully covers the decay volume to confirm the fact that there are no other accompanying particles. Most of detector components are located inside a vacuum chamber.

enable us to get very high detection efficiency against γ by applying low threshold.

In addition to the K_L decays, a π^o production by neutron interaction with detector materials is expected as another source of background. In order to avoid the process, it is needed *a pencil beam*, highly-collimated neutral beam. A new neutral beam line having well aligned thick collimator was constructed on the EP2-C line in the East Experiment Hall of the KEK 12-GeV PS in March 2000. As shown in Figure 3, the density of halo neutrons that spread out from the beam center and hit detector materials, were sup-pressed as 5 orders of magnitude from that of the beam center.

Concerning the neutron interaction, it is also needed a highly-evacuated decay volume in order to reduce the π^o production by beam neutrons with residual gas. According to a Monte Carlo study using various simulation packages, a vacuum pressure of 10^{-5} Pa is required for reduction of the background level less than 0.1 event at the sensitivity of the standard model expectation. Since a thick dead material in front of the detector would be a source of backgrounds, a differential pumping technique separating two different vacuum regions by using thin membrane is adapted. Two regions are evacuated simultaneously up to 1 Pa that is a condition to apply high voltages to the PMT. When the vacuum reaches 1 Pa level, two regions are disconnected and the decay volume in which the beam pass through is evacuated up to 10^{-5} Pa.

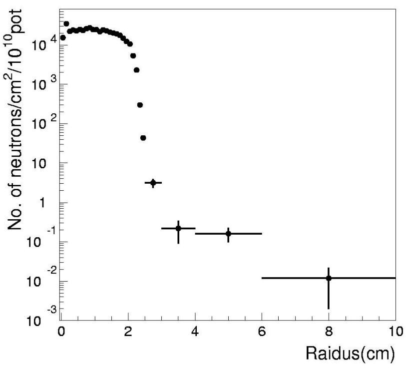

Figure 3. Monte Carlo simulation of a radial distribution of neutrons at the exit of the beam line. The halo neutrons are suppressed as 5 orders of magnitude compared with core particles, which was confirmed by successive beam surveys.

3. Data taking

Detector fabrication was completed in January 2004 and data taking started in the middle of February. Before the data taking, all detector components were tuned by using cosmic rays, which enabled us to achieve prompt optimization of the beam line elements and triggering logics.

The K_L beam were produced by 12 GeV protons hitting a 12 cm long-platinum target, where the proton intensity was 2.5×10^{12} protons per pulse of 2-second duration. The beam repetition is 4 seconds and extraction angle of the K_L beam is 4^o with respect to the primary protons. The trigger decision is done by counting the number of fixed-shape γ-clusters in the EM calorimeter. A typical triggering rate and DAQ alive time are 500 Hz and 75%, respectively. Large-size data (100 Gbytes/day) are transferred into the tape library of the KEK computer center through a Gigabit network.

There were two kinds of special studies in addition to stable data taking. One is a study of detector performance under higher rates, which was realized by shortening the beam duration down to 0.2 second. The other is a data taking for calibration of the EM calorimeter.

The calibration was done by using cosmic rays and will be improved by $K_{\pi 3}$ ($K_L \rightarrow \pi^o\pi^o\pi^o$) events using their kinematical constraints. There is, however, an ambiguity for the absolute energy scale because the process of vertex reconstruction in the $K_{\pi 3}$ decay dilutes the effects of incorrect calibration. By putting a thin aluminum plate into the beam, we can produce π^o at a fixed vertex which gives an additional constraint to obtain a proper energy scale for the calorimeter.

4. Data analysis

The first step of data analysis is an intensive study only for a small portion of data (taken during one day). Its goal is to develop analysis tools and understand detector performance. After finishing the analysis, an optimization of all kinematical cuts and veto counter thresholds will be succeeded under the principle of blind analysis[7]. The optimization and background studies will be done without touching the signal region.

A starting point of the analysis is to reconstruct well-known decay modes such as $K_{\pi 3}$, $K_{\pi 2,}$ $K_{\gamma\gamma}$ decays. As shown in Figure 5, very clean peaks are obtained in the invariant masses for both of 6 gammas (6-γ) and 4 gammas (4-γ). The peak in the 6-γ invariant mass obtained from $K_{\pi 3}$ is an important tool to study the effects of accidental hits. It is also used for a feedback of data into the Monte Carol (M.C.) simulation. The M.C. simulation well reproduces typical variables after updating the calibration of the EM calorimeter using the π^o-production data with aluminum target (see Figure 5 (c)). Also,

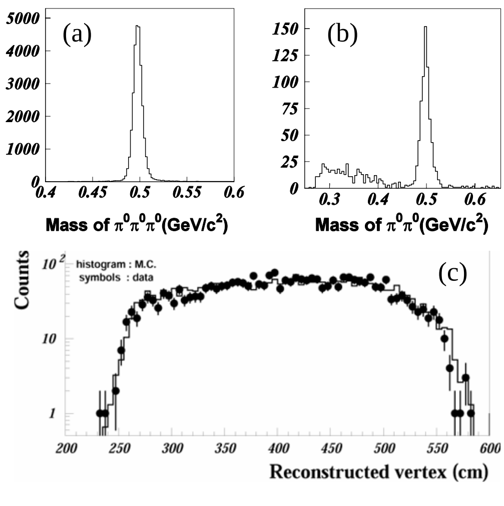

Figure 5. (a) Reconstructed 6-γ invariance mass of obtained from $K_{\pi 3}$ decays. (b) Reconstructed 4-γ invariance mass. There are a clear peak of $K_{\pi 2}$ decays and a contamination of the $K_{\pi 3}$ decays in the low mass region. (c) Reconstructed vertex distribution obtained from the $K_{\pi 3}$ decays. The Monte Carlo simulation shows good agreement with the data.

we can estimate the expected sensitivity using the reconstructed events, which is the level of 10^{-10} without considering the acceptance loss by any tight vetoing.

The analysis is moving to the veto counter study to reject events in which accompanying gammas enter veto counters. One example is 4-γ invariant masses shown in Figure 5(b). The events in the low-mass region are understood as a contamination of the $K_{\pi 3}$ decays. We are studying a cut using veto counters to suppress the events in the low-mass region without loss of the proper mass peak. Since applying tighter vetoing will cause the acceptance loss, one of main subjects in further analysis is to minimize and properly estimate it.

5. Summary and prospects

The E391a is the first dedicated experiment for the $K_L \rightarrow \pi^o \nu\nu$ decay and will become a milestone for higher-sensitivity measurement in the near future. It has finished data taking successfully in June 2004 and data analysis is being done. A rough estimation of sensitivity based on analysis using a small portion of data reaches to the level of 10^{-10} without tight vetoing. Detailed study is going on especially for the optimization of vetoing and proper estimation of acceptance for the signal aiming at making a primary result within a year.

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