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Results from the E391a experiment at KEK

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Abstract

The E391a is the first experiment dedicated to the $K_L \to \pi^0 \nu\nu$ decay. Its primary goal is to establish an experimental method which is expressed as '*pencil beam* + *hermetic veto*', for a precise measurement of this rare process. There were three times of data taking during 2004 -2005 at the 12-GeV proton synchrotron in KEK, Japan. In this article, a brief introduction and results of the E391a is reported.

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1. Introduction

The $K_L \to \pi^0 \nu\nu$ 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 related to low energy processes, a measurement of its branching ratio determines the CKM parameter, η, most accurately in the Standard Model. Also, the decay is very sensitive to the new physics beyond the Standard Model. During the last decade, theoretical studies on the decay showed remarkable achievement and there are a lot of expectations based on various new physics scenarios [1].

Experimentally, a measurement of its branching ratio is a quite challenging as it is three body decay of neutral particle (KL) into all neutral particles including two neutrinos. In addition to the limited kinematical constraints, the expected branching ratio is extremely small (2.5×10^{-11}). That is, we need to collect huge amount of KL decays which will be source of background events.

The E391a experiment, which was carried out at the KEK 12-GeV proton synchrotron, is the first experiment dedicated to the $K_L \to \pi^0 \nu\nu$ decay. Its primary goal was to establish an experimental method for a precise measurement of branching ratio of the decay. A well reconstructed single π^0 is the signature of the decay, which is detected as two-photon events. Since 99% of π^0 decay into two photons, it is essential to use $\pi^0 \to \gamma\gamma$ for high-sensitivity experiment.

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From the information of two photons measured by electromagnetic calorimeter, a π^0 was reconstructed with an assumption that the two photons were produced by the π^0 decay. After getting properly reconstructed π^0, we examined that there were no additional particles except the two photons. It was performed by a technique '*pencil beam+hermetic veto*' as to be explained below.

2. Beam line

Protons were accelerated up to the kinetic energy of 12 GeV and slowly extracted to the experimental hall during 2 seconds with 4-seconde cycles. The proton of which intensity was typically 2×10^{12} per spill, hit a production target made of platinum (Pt) rod with a length of 60 mm long and a diameter of 8 mm. The beam was extracted at an angle of 4^o with respect to the primary proton beam.

The K0 beam line was designed to provide a narrow and clean beam called a *pencil beam*. We can determine only angle between momentum vectors of two photons by using obtained information at the calorimeter with a constraint of π^0 mass. Thus, we need one more constraint for the π^0 reconstruction, which is an assumption that the π^0 decayed on the beam axis. With a beam having small cross-section (narrow beam), we can correctly determine decay vertex of π^0 and its transverse momentum (P_T) with respect to the beam. The clean beam means that it is well collimated to suppress halo neutron which was main background source.

Figure 1 shows a schematic view of beam line. The beam line consisted of two dipole magnets to sweep charged particles out of beam line and 6-stages of collimators to collimate beam. In order to control flux of photons and neutrons in the beam, movable absorbers made of 5-cm lead and 30-cm beryllium blocks were prepared.

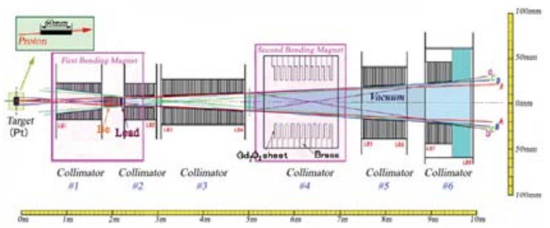

Fig. 1. Schematic view of K0 bema line for the E391a.

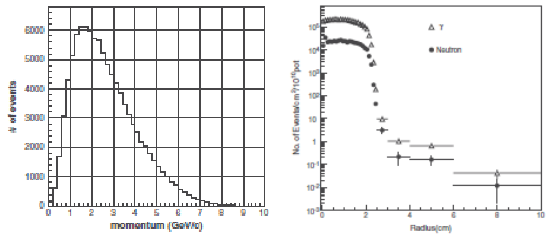

Fig. 2. Results of Monte Carlo calculation of beam line for KL momentum (Left) and profile at the exit of beam line(Right).

The KL momentum peaked around 2 GeV/c and the flux ratio of the halo to the core was lower than 10^{-5} at the exit of beam line, as shown in Figure 2. These results of beam line M.C. calculation were confirmed by the data obtained at a series of beam-survey experiments during 2000-2001 [2].

3. Detector

Figure 3 shows a schematic view of the E391a detector system. KL entered from the left side, and the detectors were cylindrically assembled along the beam axis, and most of them were installed in a large vacuum vessel.

The energies and hit positions of photons were measured by an electromagnetic calorimeter (labeled CsI in the Figure 3). It was made of 496 CsI crystals with a dimension of $7\times7\times30$ cm^3, 56 CsI crystals with trapezoidal shape and 24 modules of lead-scintillator sandwich counters forming a cylindrical shape with an outer diameter of 1.9 meters. In front of the calorimeter, a set of plastic scintillators (CV) was installed to prevent events including charged particles such as $K_L\rightarrow\pi^-e^+\nu$ from misidentifying two-photon events.

The decay region was surrounded with two large

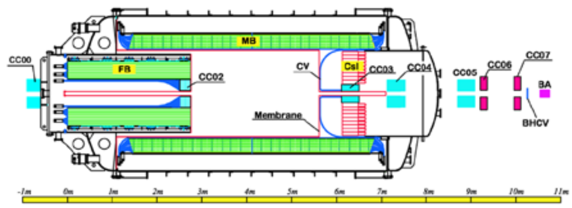

Fig. 3. Schematic view of the E391a detector.

lead-scintillator sandwich counters (MB and FB). Total thickness of MB was 13.5 radiation lengths while that of FB was 17.2. Wave-length-shifting fibers were used for read-out of the counters in order to reduce the light attenuation in the long scintillators.

A serious of counters surrounded the beam hole in order to detect photons escaping with a small angle from the beam direction. Four different types of detectors were prepared according to their position and function; CC02 (lead-scintillator shashlik type sampling calorimeter), CC03 (tungsten-scintillator sandwich counter), CC04 and CC05 (lead-scintillator sandwich counter), and CC06 and CC07 (lead glass crystal). All the collar counters satisfied the requirement that the light output be more than 10 photoelectrons per 1-MeV energy deposit, which was the typical energy threshold for vetoing.

A beam-plug counter, back-anti (BA), was located at the end of detector system along the beam axis in order to detect photons escaping through the beam hole. It consisted of six modules, where each module had six alternating lead-scintillator layer and a single layer of quartz. In the last data taking (Run-III), lead-scintillator layers were replaced by PWO crystals with the intention to separate electromagnetic showers from the neutron hits. A thin layer of plastic scintillators, the beam hole charged veto (BHCP), was placed in front of the BA.

4. Data taking and Analysis

The E391a experiment started data taking in February 2004. In the first data taking (Run-I), the membrane for vacuum separation drooped into the beam near the calorimeter and caused many neutron-induced backgrounds [3]. After fixing this problem, we took data twice during February-April (Run-II) and October-December (Run III) in 2005 [4].

Trigger was determined by summed signal of eight neighboring CsI crystals grouped into 72 regions, in total. It was required that there were at least two summed signals above the threshold (~ 60 MeV energy deposit) and anticoincidence of several veto counters. The trigger enabled us to collect data not only for the $K_L \to \pi^0 \nu\nu$ decay but also for the $K_L \to \pi^0\pi^0$ and $K_L \to \pi^0\pi^0\pi^0$ decays which were used as a normalization and performance check of the detector components

Data were collected through multiple parallel systems of VME bus, each of which was operated with a CPU for control. The dead time of the DAQ system was around 600μs/event and the triggering rate was 300 per spill (150 Hz). The data size was 3 Mbytes/spill and the typical data size collected per day was 60 GB.

The data analysis started from clustering which connected neighboring CsI crystals to obtain energy and position of incident photon. The spread of shower should be consistent with obtained energy and position to become photon cluster. After selecting events that had exactly two photons in the calorimeter, we required that there were no additional in-time hits in all veto counters. Then, we could calculated the decay vertex along the beam axis (Z_{vtx}) and the transverse momentum (P_T) of π^0. The reconstructed π^0 should be kinematically consistent with a $K_L \to \pi^0 \nu\nu$ decay within proper KL momentum range. Finally, we defined the signal region for a candidate event in the P_T-Z_{vtx} plane to be $340 \leqq Z_{vtx} \leqq 500$ cm and $0.12 \leqq P_T \leqq 0.24$ GeV/c.

5. Background Estimation

There were two types of background source, KL decays and neutron interactions. The $K_L \to \pi^0\pi^0$ ($K_{\pi2}$) decay is considered as a main background source due to the KL decays. The $K_{\pi2}$ decay will be misidentified as a signal when we miss two photons. That is, we have to detector additional photons with veto counters to reject the background.

GEANT3 based Monte Carlo (M.C.) simulation was used to estimate the amount of the $K_{\pi2}$ background. We applied same selection cuts to the M.C. data which was 70 (60) times larger than that of Run-II (Run-III) data. There were two events in Run-II M.C. data and no event in Run-III M.C. data, which gave background estimation as $(2.4 \pm 1.8_{stat} \pm 0.2_{syst}) \times 10^{-2}$.

Validity of the M.C. simulation was test by four-photon data samples, which were generated by $K_L \to \pi^0\pi^0$ ($K_{\pi2}$) and $K_L \to \pi^0\pi^0\pi^0$ ($K_{\pi3}$) decays. As shown in Figure 4, M.C. data was well reproduced obtained data especially lower mass tail. Since the lower mass

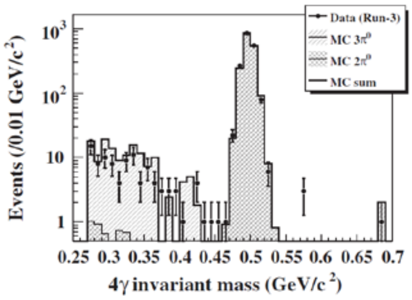

Fig. 4. Reconstructed 4 photon invariant mass.

tail was produced due to missing two photons among six photons in the $K_{\pi3}$ decay, which was the same situation that the $K_{\pi2}$ decay became background.

When a neutron interacts with materials, a single π^0 is produced and become background event. In order to remove π^0 production by neutron interaction with air, the decay region should be evacuated. When a neutron enters detector apart from beam center (halo neutron), a single π^0 is produced as a result of interaction with detector materials. Since the detector position is fixed, we need to define signal box far from the detector position.

In order to estimate neutron backgrounds, we used a combined M.C. calculation with GEANT3 and FLUKA codes for better reproducibility. The validity of M.C. calculation was tested by using special data set in which a 5-mm-thick aluminum plate was inserted into the beam behind CC02. The special run provided large amount π^0 and η events generated by neutron interaction with the aluminum plate. The good agreement between M.C. calculation and data at the special run enabled us to use the M.C. calculation for the background estimation.

There were three main sources of backgrounds, π^0 produced by the CC02 and by the CV, and η produced at the CV. The CC02-π^0 and the CV–π^0 was due to wrong measurement of photon energy caused by shower leakage or pile up of accompanying particles. In the CV-η events, the reconstructed vertex shifted to the signal region even though it was generated downstream of the signal region due to its mass which was heavier than π^0 mass used in the calculation. We estimated the background as 0.66 (CC02-π^0), less than 0.36 (CV-π^0) and 0.19 (CV-η), respectively.

6. Results and discussion

The number of KL was obtained from the $K_L \to \pi^0\pi^0$ decay as 8.70×10^9 for the combined sample of Run-II and Run-III, which gives single event sensitivity as 1.11×10^{-9}.

After finalizing all of the event selection cuts, the candidate events inside the signal box were examined. No events were observed in the signal region, as shown in Figure. 5. Based on Poisson statistics, an upper limit for a branching ration of the $K_L \to \pi^0\nu\nu$ was set to 2.6×10^{-8} at the 90% confidence level.

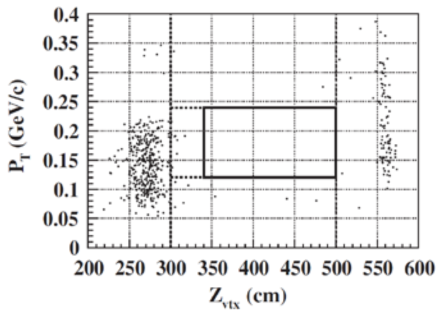

Fig. 5. Scatter plot of P_T vs Z_{vtx} for the events after applying all selection cuts. The box indicates the signal region of $K_L\to\pi^0\nu\nu$ decay.

Even though the result is still far from the Standard Model expectation, the E391a showed that the detection method "*pencil beam + hermetic veto*" would work properly in higher sensitivity experiment, and clarified background sources related to neutrons. Based on the E391a results, the next step, KOTO [5], is preparing at J-PARC with updated E391a detector applying needed upgrades aiming at the first observation of the events without the neutron related backgrounds.

References

[1] http://www.lnf.infn.it/wg/vus/content/Krare.html
[2] H. Watanabe et al., NIM A545, 542 (2005).
[3] J.K.Ahn et al., Phys. Rev. D74, 052205(R) (2006).
[4] J.K.Ahn et al.,Phys. Rev. Lett 100, 291892 (2008). J.K.Ahn et al.,Phys. Rev. D81, 072004 (2010).
[5] G.Y.Lim, Talk in this conference.