E391a: Study of the rare decay $K_L \to \pi^0\nu\bar{\nu}$

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I. MOTIVATION

The $K_L^0 \to \pi^0\nu\bar{\nu}$ decay has been considered as a golden-plated channel in K-decays. In the standard model (SM) the decay amplitude is proportional to ImV_{td}, where V_{td} is one of the CKM matrix elements, which has not been directly measured. On the other hand the branching ratio of the $K_L^0 \to \pi^0\nu\bar{\nu}$ decay is predicted to be $(2.49 \pm 0.39) \times 10^{-11}$ by SM using the constraint of unitarity among the CKM parameters determined by B-decays. It is quite interesting that the uncertainty already reaches $\pm 15\%$. Thus, we may say that the goal of experiment should not be a simple additional measurement of ImV_{td}, but a search for a deviation from the SM prediction due to new physics.

The $K_L^0 \to \pi^0\nu\bar{\nu}$ decay has remarkable merits in the search for the deviation. The decay purely proceeds through the electro-weak FCNC (Flavor Changing Neutral Current) and the theoretical ambiguity is very small. For example, a $K_L^0 \to \pi^0\nu\bar{\nu}$ measurement at the sensitivity of 3×10^{-13}, which corresponds to an observation of 100 SM-events, can clarify the deviation as a 5σ effect when the branching ratio is enhanced by new physics by a factor of 1.75. Such enhancement can be generated at the 100 TeV mass scale by a new boson at the tree diagram. In the case of $B \to X_s\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$, which are golden plated channels in the new-physics searches at LHCb, the 1.75 enhancement can be brought by the 10 TeV scale in the similar model. The $K_L^0 \to \pi^0\nu\bar{\nu}$ decay is thereby to search for new physics in wider region (higher mass scale) than other processes.

Since the charged mode, $K^+ \to \pi^+\nu\bar{\nu}$, has similar merits as $K_L^0 \to \pi^0\nu\bar{\nu}$, we may find a deviation as shown in Figure 1.

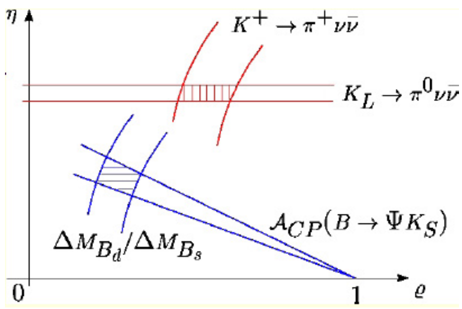

FIG. 1: One possible scenario: difference of CKM parameters determined by K decays and B decays

II. EXPERIMENTAL METHOD AND THE GOAL OF E391A

The main problem exists in the experiment side: how to measure the rare decay $K_L^0 \to \pi^0\nu\bar{\nu}$ and how to distinguish it from an enoumous mount of expected backgrounds. E391a is the first dedicated experiment for $K_L^0 \to \pi^0\nu\bar{\nu}$ in contrast with the several trials for the charged mode in the past. Although the neutral mode has several advantages such as no $K_{\mu 2}$ and the smaller branching ratio of $K_{\pi 2}$, it has the disadvantages such as relatively poor resolution for a separation of the regions of signal and background and no tracking devices for photons. Thus, we took a simple approach to keep acceptance, which is crucial for rare decay experiment. We used a collimated beam (pencil beam) to define the beam axis, a calorimeter to measure the energies and hit positions of two photons from π^0 precisely and a hermetic coverage around the decay region with detectors having a high detection efficiency to veto other processes accompanying additional particles. The decay vertex (Z_{vtx}) and the missing transverse momentum (P_T) were calculated with the assumption that the two-photons are from π^0 decay on the beam axis. Contaminations by other prcesses were reduced by a selection of higher P_T events and the veto cut. The method was focused on the elimination of background, and it is different from that for the charged mode, which mainly uses a kinematical separation.

Figure 2 shows the experimental setup of E391a. The detectors, which were clyndrically arranged, were installed in a large vacuum vessel.

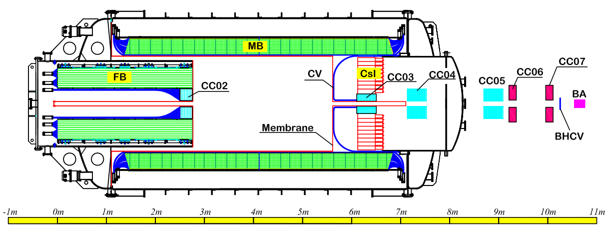

FIG. 2: Experimental setup of E391a.

E391a had two goals in the proposal: to confirm the experimental method, and to reach a sensitivity below the Grossman-Nir limit, which is 1.7×10^{-9} determined indirectly from the charged mode.

III. DATA TAKING AND ANALYSIS

After the major construction of detectors from 2001 to 2003, we had three periods of data taking (Run 1, 2 and 3) from February 2004 to November 2005. The numbers of primary protons on the K_L^0 production target (POT) were about 3×10^{18}, 2×10^{18} and 1.5×10^{18} in Run 1, 2 and 3, respectively. We refined the experimental and running conditions step-by-step.

The first result using one-week sample of Run 1, in which we obtained the upper limit 2.1×10^{-7} and exceeded the previous value by a factor of three, was published [1]. The analysis of the full sample of Run 1 is almost finished now. It cannot improve the one-week result so much due to the background which were produced from a part of the membrane (a vacuum separator) hanged over the beam during Run 1; the analysis, however, provided a chance for deeper understanding about background behaviors and for confirming the one-week result through a blind analysis. We plan to publish the result using the Run 1 full sample. The analysis of the full sample of Run 2 is also finished and will be published soon. The running condition of Run 2 was better than that of Run 1, after repairing the hanging membrane, by using the tuned parameters of the data taking *etc.* The Run 3 analysis is now extensively going on.

IV. PRELIMINARY RESULT OF THE RUN 2 ANALYSIS

Figures 3 shows a preliminary plot of Z_{vtx} vs P_T using one-third sample of Run 2 [2].

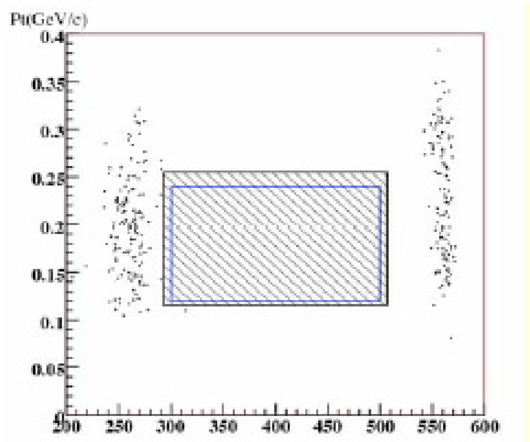

FIG. 3: Z_{vtx} vs P_T plot for the Run-2 1/3 sample. The signal box is still masked for blind analysis.

There is no event in the surrounding regions except for the up- and down-stream Z_{vtx}, which correspond to the positions of the collar counter CC02 and the veto counter for charged particls CV, respectively. Those counters have a small aperture for beam; in other word, they were the materials placed in the halo beam near the beam axis. The event clusters are consistent with the π^0's produced by interactions of beam halo with those counters. $K_L^0 \to \pi^0 \nu \bar{\nu}$ decays are expected to be seen as shown in Figure 4 with the same selction criteria.

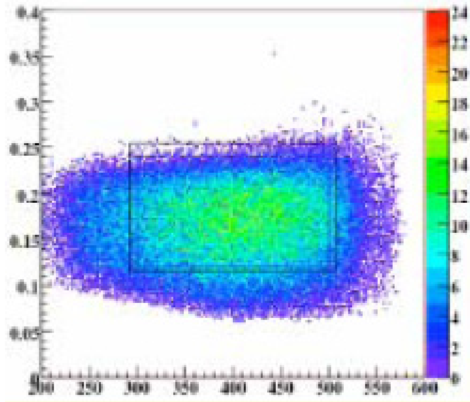

FIG. 4: Z_{vtx} vs P_T plot for Monte Carlo $K_L^0 \to \pi^0 \nu \bar{\nu}$ decays selected by the same criteria with data

The sensitivity for this sample is estimated to be about 9×10^{-8}.

V. EXTENTION TO J-PARC

The E14 experiment at J-Parc [3] is a plan to reach a sensitivity of $O(10^{-12})$ using the intense beam of one hundred times larger than KEK-PS. E14 was granted the first examination in 2006 and was fully-approved by the PAC in July 2007. We hope that it will be one of the first experiments at the Hadron Hall of J-Parc from 2009. The design concept of E14 is to recycle all possible devices of E391a, and to modify them, where the modification is considered to be crucial for reducing background further and for being tolerable against the expected high-rates. The major modifications are the replacement of the CsI calorimeter into the thick and finely-segmented one used in KTeV, the upgrade of readout electronics to wave-form digitizer and the replacement of the beam plug counter to the new one, which has been designed for KOPIO. The collaboration expects that the contaminations by halo beam interactions can be reduce to a negligible level, using less halo and better K/n at the new beam line in J-Parc, optimizing the apertures of collar counters, *etc.* These design studies were performed based on experimental data of E391a and simulation codes developed for E391a. We have a plan of the second step in J-Parc to reach a sensitivity of $O(10^{-13})$.

VI. SUMMARY

Although it is too early to make a concluding summary of E391a, it is worth reviewing how we have achieved the goal of E391a. The first goal or purpose, which is the confirmation of the experimental method, would be done rather perfectly. There were many technical problems such as the pencil beam, very high vacuum of 10^{-5} Pa to reduce π^0 productions in the decay region by beam-air interactions, very tight veto with a threshold down to the 1 MeV level to reduce background, *etc.* In those problems we also found answers. We also developed several software, procedures of calibration, various codes for analysis and simulation, *etc.* Information of the counting rates at 1 MeV level was also very valuable for the design of E14.

On the other hand, we must probably say that the second goal, to reach the Grossmann-Nir limit, will not be achieved, although the Run 3 analysis is still in progress. It was mainly caused by a large acceptance loss. The event selection criteria had to be tighter than expected in order to reduce the background caused by beam interactions with the materials around the beam. Typical background was multi-π^0 productions at the drooping membrane in Run 1, and η production at the charged veto counter CV in Run 2. We found that the former could be reduced by tightening the beam plug counter BA, which means the vetoing with a wider time window to prevent a masking effect, where the masking happens during an early-time pulse width. However, it sacrificed the acceptance much for Run 1, because of the longer pulse width of the BA discriminater in Run 1. The latter was caused by the wrong positioning of CV. The CV should not have covered the collar counter CC03, which was only used for veto. It should have been located more outside (far from the beam axis). Another serious background throughout the runs was the tail of CC02 events. The CC02 events were increased by the sampling structure of CC02, which missed to detect small activity of recoil after interactions, and the tail was caused with the shower leakage due to short depth of the CsI calorimeter. These were carefully reflected to the E14 design.

Then, we may conclude that we have learned a lot even from the results which do not reach the Grossman-Nir limit.

[1] Phys. Rev. D74, 051105(R) (2006).
[2] From talks by T. Sumida and G. Perdue for E391a at KAON07 (http://www.lnf.ifnn.it/conference/kaon07/). We will report an up-date plot at the presentation in the review committee.
[3] P14 proposal, *Proposal for* $K_L^0 \to \pi^0\nu\bar{\nu}$ *Experiment at J-Parc*, exists in http://j-parc.jp/Nucl Part/Proposal.e-html.