PROCEEDINGS OF SCIENCE

$K^+ \to \pi^+ \nu \bar{\nu}$ & Other Semileptonic Kaon Decays

Zhe Wang[*†]
Brookhaven National Laboratory
E-mail: wangzhe@bnl.gov

This is a brief summary of the theoretical interest and recent experimental progress on $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L^0 \to \pi^0 \nu \bar{\nu}$, $K_L^0 \to \pi^0 e^+ e^-$, $K_L^0 \to \pi^0 \mu^+ \mu^-$, as well as kaon lepton-flavor-violating (LFV) semileptonic decays. Experiment E949 published a final result of the search for rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay. The branching ratio was measured to be $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$. The central value is twice that of the SM prediction, but still consistent within errors. Experiment E391a presented a new upper limit for the decay of $K_L^0 \to \pi^0 \nu \bar{\nu}$ which is $< 6.7 \times 10^{-8}$ $C.L. = 90\%$.

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[*]Speaker.

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1. Introduction

Over the past 60 years the study of production and decays of K mesons has been one of the most productive fields in particle physics. The diversity of the quark spectrum was first indicated by the discovery of the K meson [1]. Some time later the "$\theta - \tau$ puzzle" in the kaon system led to the famous discovery of parity violation [2]. Kaon physics remains one of the most revealing subjects at the frontier of particle physics, including the study of flavor dymanics and searches for new physics beyond the Standard Model (SM). This article focuses on recent results in flavor-changing neutral-current (FCNC) kaon decays. The search for kaon lepton-flavor-violating (LFV) semileptonic decays is also summarized.

2. Flavor Changing Neutral Current

2.1 Theory

The rare decays $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ are theoretically very clean and highly sensitive to short distance physics. They provide a critical test for the Cabibbo-Kobayashi-Maskawa (CKM) mechanism of CP violation. For these reasons, they play an outstanding role among FCNC processes both in the SM and its extensions [3].

$K^+ \to \pi^+ \nu\bar{\nu}$ is forbidden to first order in the SM because it involves a FCNC interaction. It is, however, allowed via higher order weak interactions, but with a considerably lower rate than the other ordinary weak interaction processes. In the SM this process is mediated by the electroweak penguin and box diagrams depicted in Fig. 1. This implies that the non-perturbative effects are severely suppressed and that the low energy effective Hamiltonian [4, 3]

$$\mathscr{H}_{eff} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \sum_{l=e,\mu,\tau} (\lambda_c X^l(x_c) + \lambda_t X(x_t))(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{lL} \gamma^\mu \nu_{lL})$$

can be described in terms of a single effective operator $Q_{sd}^{\nu\nu} = (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{lL} \gamma^\mu \nu_{lL})$ [5]. Here G_F is the Fermi constant, α the electromagnetic coupling and θ_W the weak mixing angle. The sum is over all lepton flavors. $\lambda_i = V_{is}^* V_{id}$ are the CKM factors and f_L represent the left-handed fermion fields. The coefficient $X^l(x_c)$ ($X(x_t)$) is the kinematic function of charm (top) quark mass giving the contribution from the charm (top) quark. While deriving the branching ratio with this $\mathscr{H}_{eff}$, the relevant hadronic matrix element can be extracted from the measurement of the branching ratio of $K^+ \to \pi^0 e^+ \nu$ with the consideration of isospin symmetry. The top quark in the loops dominates the transition because of its heavy mass, and hence the quantity

$$V_{ts}^* V_{td} = -A^2 \lambda^5 (1 - \rho - i\eta)$$

is measured. With the A and λ well-measured, ρ and η can be determined by the branching ratio. A recent prediction for the branching ratio of this process is $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$ [6] where the quoted uncertainty is dominated by the uncertainty in CKM matrix elements.

$K_L^0 \to \pi^0 \nu\bar{\nu}$ is unique in that it is completely dominated by direct CP violation [7]. The effective Hamiltonian is the same as $K^+ \to \pi^+ \nu\bar{\nu}$. However, since K_L^0 is predominantly a coherent and CP odd superposition of K^0 and $\overline{K^0}$; only the imaginary part, η, of $V_{ts}^* V_{td}$ survives in the

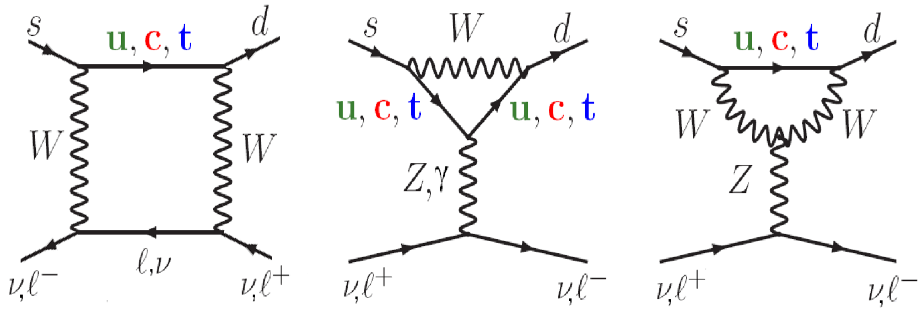

Figure 1: Short-distance contributions to $K \to \pi\nu\bar{\nu}$ and $\pi l^+ l^-$ mediated by the electroweak box and penguin diagrams where l stands for charged lepton. Note that in the second diagram, γ only contributes to the $l^+ l^-$ final state.

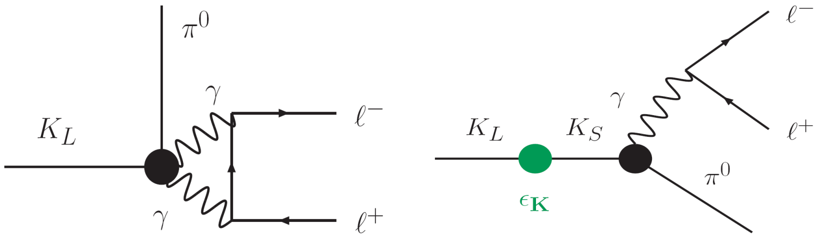

Figure 2: The CP conserving contribution through the $\pi^0\gamma^*\gamma^*$ intermediate state (left) and the indirectly CP violating contribution induced by K^0-$\bar{K}^0$ mixing (right).

amplitude. The branching ratio $Br(K_L^0 \to \pi^0\nu\bar{\nu})$ is directly proportional to η^2. The measurement of $Br(K_L^0 \to \pi^0\nu\bar{\nu})$ and $Br(K^+ \to \pi^+\nu\bar{\nu})$ can determine the CKM triangle independently of any other B measurements. The lack of a significant charm quark contribution reduces the intrinsic theoretical uncertainty to $\mathscr{O}(2\%)$. The $Br(K_L^0 \to \pi^0\nu\bar{\nu})$ is predicted to be $(2.49 \pm 0.39) \times 10^{-11}$ [8].

The $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \mu^+ \mu^-$ processes are also sensitive tests of the SM. There are three expected contributions to the amplitude in the SM: direct CP violating contributions from electroweak penguins and a W box diagram as shown in Fig. 1; a CP conserving contribution which proceeds through the $\pi^0\gamma^*\gamma^*$ intermediate state; and an indirectly CP violating contribution from $K_S^0 \to \pi^0 l^+ l^-$ shown in Fig. 2 (The interference between direct and indirect CP violating components also needs to be considered). The remarkable point with the last two contributions is that they can be entirely determined by experimental data of $K_L^0 \to \pi^0\gamma\gamma$ and $K_S^0 \to \pi^0 l^+ l^-$. Recent theoretical work [9, 10] shows that the CP conserving contribution is negligible in the e^+e^- channel, and represents only 30% of the total rate in the $\mu^+\mu^-$ channel. The predictions [10] for the branching ratios are $Br(K_L^0 \to \pi^0 e^+ e^-) = (3.5^{+1.0}_{-0.9}) \times 10^{-11}$ and $Br(K_L^0 \to \pi^0 \mu^+ \mu^-) = (1.4 \pm 0.3) \times 10^{-11}$. The decays $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \mu^+ \mu^-$ are sensitive to different combinations of short-distance FCNC components. Charged lepton and neutrino may have different couplings to intermediate particles in new physics. Though not as theoretically clean as the golden mode $K \to \pi\nu\bar{\nu}$, they still offer an invaluable window into new physics.

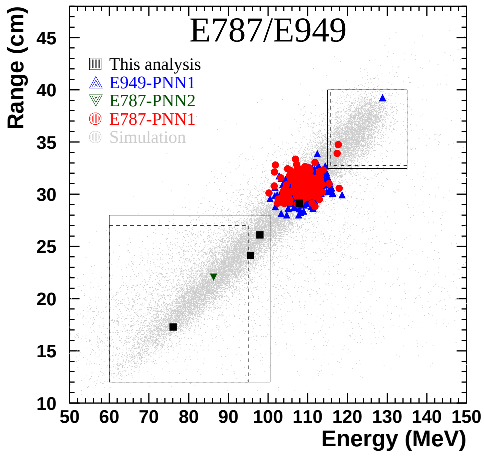

Figure 3: Kinetic energy vs range of the all seven candidates from E787/E949 experiment. The four boxes (solid or dashed) indicate the signal region of each analysis.

2.2 $K^+ \to \pi^+ \nu\bar{\nu}$ Experimental Result from E949

Recently experiment E949 [11] at BNL published their new result [12, 13] on the experimental research of $K^+ \to \pi^+ \nu\bar{\nu}$ in the region $140 < P_\pi < 199$ MeV/c.

Low energy K^+ is stopped in the target in the center of E949 detector and decay at rest. Although a neutrino and an antineutrino are emitted in the process, these particles interact too weakly to be detected. A single kaon and a delayed positively charged pion are the signature of a signal of 'one in ten billion' decay. With the most efficient particle detector system ever built, as well as the modern analysis effort, blind or unbiased analysis techniques, the total background was suppressed by a factor of 10^{11} and was precisely predicted to be $0.93 \pm 0.17(stat.)^{+0.32}_{-0.24}(syst.)$.

Three new candidates were observed bringing the total number to seven; the other four of which were found in previous searches by E949 and its predecessor experiment E787. The seven candidates and the SM simulation result are shown in Fig. 3. This results in a branching ratio $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ with a central value twice that of the SM prediction, but that is still consistent within errors.

2.3 $K^0_L \to \pi^0 \nu\bar{\nu}$ Experimental Result from E391a

KEK E391a is the first experiment dedicated to the $K^0_L \to \pi^0 \nu\bar{\nu}$ decay. The experimental signature of the $K^0_L \to \pi^0 \nu\bar{\nu}$ decay mode is comprised of exactly two photons with the invariant mass of a π^0 and nothing else. A highly collimated "pencil" K^0_L beam was adopted to provide transverse constraint on the origin of π^0. The detector includes a calorimeter composed of an array of high-resolution pure CsI modules to measure the two photons from π^0 decay with a nearly hermetic veto system to veto any other activity. Events with two clusters in the CsI calorimeter unaccompanied by other detector activity were selected. Assuming that two photons came from a π^0 decay on the beam axis, the decay vertex position along the beam axis, Z, and the transverse

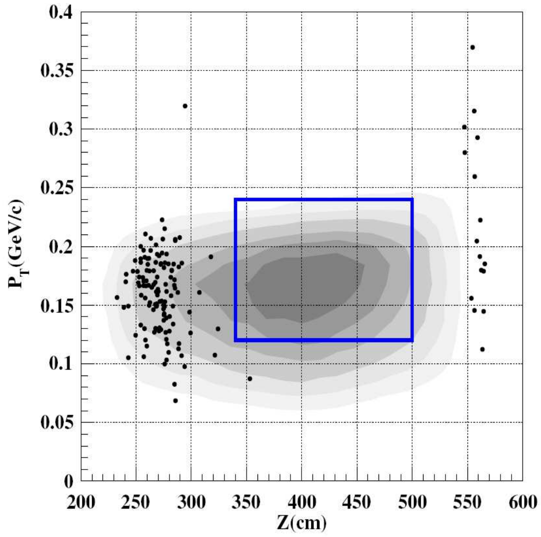

Figure 4: $K_L^0 \to \pi^0 \nu\bar{\nu}$ Experimental Result from E391a. Scatter plot of P_T versus reconstructed Z position after imposing all the cuts. The points show the data and the contour represents the simulated distribution of the signal. The rectangle indicates the signal region.

momentum, P_T, were calculated. The signal region ($0.12 < P_T < 0.24$ GeV/c and $340 < Z < 500$ cm) was examined after all selection criteria were determined. The scatter plot with all cuts applied except the P_T and Z is shown in Fig. 4. The main background source from K_L^0 decays was the $K_L^0 \to \pi^0\pi^0$ mode. Beam halo neutrons also induced a substantial portion of background, although neutron flux in the halo was suppressed by five orders of magnitude from the beam core. An upper limit on the branching ratio was set to be 6.7×10^{-8} at the 90% level [14].

2.4 $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \mu^+ \mu^-$ Experimental Results from KTeV

The best $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \mu^+ \mu^-$ upper limits ($Br(K_L^0 \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$ [15] and $Br(K_L^0 \to \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$ [16]) are still given by experiment KTeV at Fermi Lab.

2.5 Prospects for Measuring $K^+ \to \pi^+ \nu\bar{\nu}$

The sensitivity of the E787/E949 results was limited by low statistics, since a total of only seven candidates were found. The main background mechanism included the scattering of charged track in target region which resulted in the track's momentum reconstructed incorrectly, and the inefficiency of low energy particle detection, for example, radiative photons and particles from multi-body kaon decays.

NA62 [17, 18] at CERN is taking another approach and addressing these shortcomings. They are now preparing a new detector to collect $\sim$100 $K^+ \to \pi^+ \nu\bar{\nu}$ events in two years (2011-2012) for a measurement of the branching ratio with accuracy of 10% with S/N $\sim$10/1. An intense (800 MHz rate) high momentum (75 GeV/c) K^+ beam will be produced to satisfy the statistical requirement of the proposal. K^+ will decay in-flight so background introduced by the stopping target can be avoided. Low energy decay products in the rest frame of the K^+ will be boosted forward. For

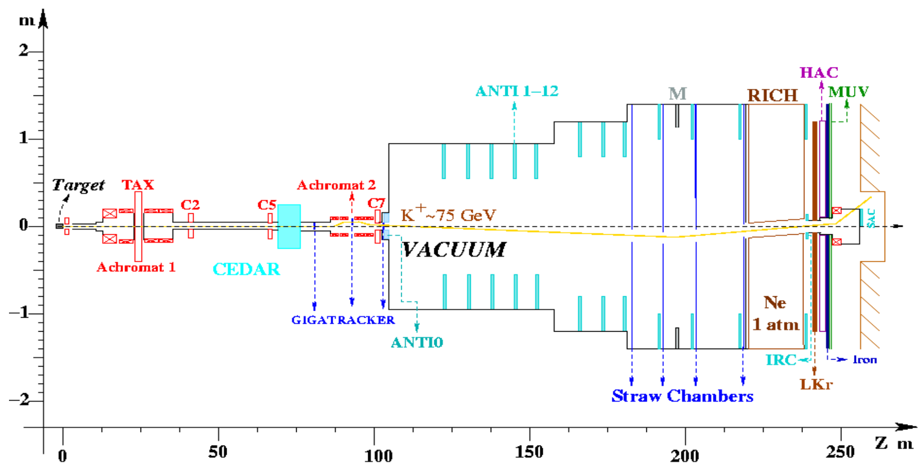

Figure 5: Layout of the proposed NA62 detector

example, the momentum of the π^0 from a $K^+ \to \pi^+\pi^0$ transition is above 40 GeV/c which can hardly be missed. A schematic diagram of NA62 experiment is shown in Fig. 5.

This project received strong support from CERN and INFN with significant funding deployed for the R&D phase [19] and was approved by the CERN Research Board on Dec. 5, 2008.

2.6 Prospects for Measuring $K_L^0 \to \pi^0\nu\bar{\nu}$

With all the experience accumulated from E391a the construction of a new detector E14 [20] and a new beamline at J-PARC is in progress aiming at 2.8 $K_L^0 \to \pi^0\nu\bar{\nu}$ events. The proposed sensitivity is three orders of magnitude better than E391a. To achieve this significant improvement the $Flux \times Runtime \times Acceptance$ of the new high intensity beam line will be 3000 times that of E391a's design. The halo neutron to K_L^0 ratio is designed to be suppressed by a factor of 240 compared to E391a. The granularity of the CsI calorimeter will be finer and each crystal will be longer for better position resolution and to reduce leakage. The first physics run is scheduled in 2011.

3. Lepton-Flavor-Violating Semileptonic Kaon decays

In the SM of particle physics LFV decays are possible with nonzero neutrino masses and mixing, but the rates for such decays are far beyond the reach of any current experiment. Therefore, the observation of LFV decays would be an indication of new physics. Some interesting reviews can be found in [21, 22]. Although current searches can only present upper limits for these decay modes, they still provide important constraints for the scale of new physics. The KTeV collaboration recently published their new results for $K_L^0 \to \pi^0\mu^\pm e^\mp$ and $K_L^0 \to \pi^0\pi^0\mu^\pm e^\mp$. Table 1 is a compilation of current experimental limits for LFV semileptonic kaon decays. The experimental sensitivity has reached the level of $10^{-9} \sim 10^{-11}$.

Decay mode	Upper limit	
$K_L^0 \to \pi^0\mu^\pm e^\mp$	$< 7.6\times10^{-11}$	KTeV [23]
$K_L^0 \to \pi^0\pi^0\mu^\pm e^\mp$	$< 1.7\times10^{-10}$	KTeV [23]
$K^+ \to \pi^+\mu^+e^-$	$< 1.3\times10^{-11}$	Combined by PDG [24]
$K^+ \to \pi^+\mu^-e^+$	$< 5.2\times10^{-10}$	E865 [25]
$K^+ \to \pi^-\mu^+e^+$	$< 5.0\times10^{-10}$	E865 [25]
$K^+ \to \pi^-\mu^+\mu^+$	$< 6.4\times10^{-10}$	E865 [25]
$K^+ \to \pi^-e^+e^+$	$< 3.0\times10^{-9}$	E865 [25]

Table 1: Current experimental results for LFV semileptonic kaon decays

4. Summary

In the theory of the SM the rare FCNC kaon decays are tightly bound with direct CP violation. With sophisticated technology and analysis methods, the E787/E949 experiment is the first to reach the sensitivity of the SM prediction and found seven $K^+ \to \pi^+\nu\bar{\nu}$ candidates. Experiment E391a had also made a steady step towards the discovery of $K_L^0 \to \pi^0\nu\bar{\nu}$. The new projects of NA62 and E14 show a very promising prospect for achieving high precision measurements of rare kaon decays. The experimental sensitivity for searching semileptonic LFV kaon decays has reached the level of $10^{-9} \sim 10^{-11}$.

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