



Rare Kaon Decays

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Abstract. There has been great recent progress in measurements of rare and ultra-rare kaon decays, particularly those involving flavor changing neutral currents. I review here those recent results and the prospects for future measurements.

INTRODUCTION

The subject of rare and ultra-rare kaons decays is very active at this time with 8 experiments from 4 labs reporting new results recently and 6 new experiments recently approved. The physics topics under study include flavor changing neutral currents (FCNC), measurements of direct and indirect CP violation and searches for lepton flavor violation (LFV). These measurements are all characterized by very high sensitivities, studying modes with branching ratios in the $10^{-7} - 10^{-12}$ range with single event sensitivities approaching 10^{-12} . This is a region of sensitivity beyond the reach of charm and B experiment, at least for now. The development of beams with fluxes well above $1MHz$ of kaon decays enable these experiments. In this paper I will cover some of the important new results and the goals for the new experiments.

FLAVOR CHANGING NEUTRAL CURRENTS

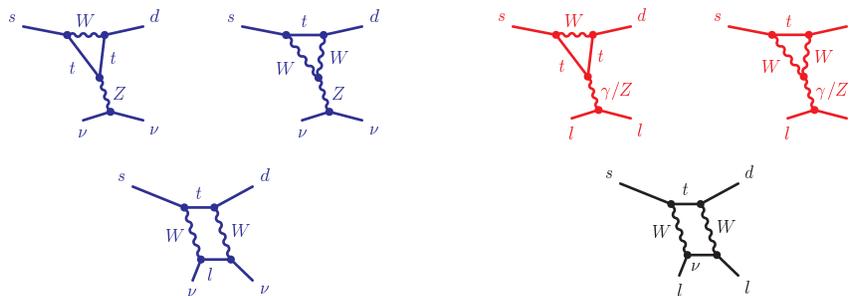


FIGURE 1. FCNC Feynman diagrams.

The flavor changing neutral currents in leptonic kaon decay, shown in Fig. 1, always involve at least two electroweak currents and an up type quark loop. These short distance amplitudes tend to be dominated by top quarks in the loops, which give direct access to $\lambda_t = V_{ts}^* V_{td} = A\lambda^5(1 - \rho - i\eta)$ the complex parameter of the CKM matrix, V_{td}

which controls CP violation in the Standard Model. Decay modes where long distance amplitudes are small or absent become laboratories to directly measure λ_t .

As an example of the state of the art in ultra-rare decays the E871 experiment at BNL has published the rate of the rarest decay mode every observed, $\text{Br}[K_L \rightarrow e^+e^-] = (8.7_{-4.7}^{+5.7}) \times 10^{-12}$ [1] with 4 clean events and a 6200 events signal for the relatively *common* mode $\text{Br}[K_L \rightarrow \mu^+\mu^-] = (7.18 \pm 0.17) \times 10^{-9}$ [2]. These signals are shown in Fig. 2. These dilepton modes are dominated by long distance $K_L \rightarrow \gamma^*\gamma^*$ diagrams. The unitary bound from these long distance diagrams saturates the $K_L \rightarrow \mu^+\mu^-$ rate observed leaving little room for short distance effects like V_{td} . The main goal of this experiment was the search for the LFV mode $K_L \rightarrow \mu^\pm e^\mp$ where E871 set a limit of $\text{Br}[K_L \rightarrow \mu^\pm e^\mp] < 4.7 \times 10^{-12}$ [3]

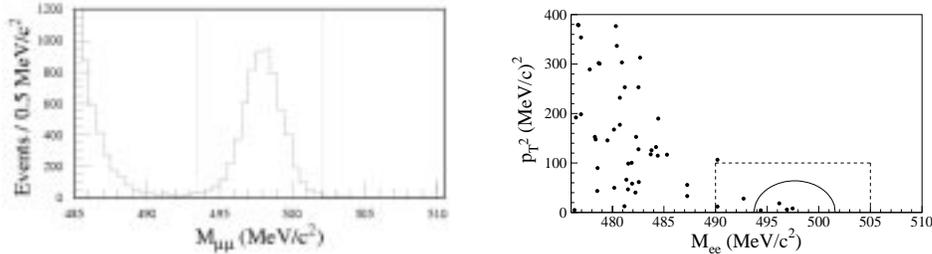


FIGURE 2. E871 signals for a) $K_L \rightarrow \mu^+\mu^-$ b) $K_L \rightarrow e^+e^-$.

KTeV at Fermilab has searched for $K_L \rightarrow \pi^0 l^+ l^-$ and set a limit of $\text{Br}[K_L \rightarrow \pi^0 \mu^+ \mu^-] < 3.8 \times 10^{-10}$ [4] and $\text{Br}[K_L \rightarrow \pi^0 e^+ e^-] < 5.1 \times 10^{-10}$ [5] in both case observing 2 events expecting about 1 background in their signal box. The Standard Model prediction for the direct CP violation contribution to $K_L \rightarrow \pi^0 e^+ e^-$ is $(4.3 \pm 2.1) \times 10^{-12}$. These measurements are getting close to the interesting region. There are also CP conserving and indirect CP violating contributions to these modes. V_{td} must be extracted once these modes are reliably measured.

NA48 at CERN has undertaken a program to measure $K_S \rightarrow \pi^0 e^+ e^-$ to help with this extraction. In a two day test run they set a limit of $\text{Br}[K_S \rightarrow \pi^0 e^+ e^-] < 1.4 \times 10^{-7}$ [6]. The Standard Model prediction for $K_S \rightarrow \pi^0 e^+ e^-$ is $\sim 5 \times 10^{-9}$. The measurement of this mode is a major goal of the approved NA48/1 [7] run. They expect a $\times 50$ improvement with 120 days of running to achieve a sensitivity of $\sim 3 \times 10^{-9}$, in the Standard Model range.

There have been 3 measurements of $\text{Br}[K^+ \rightarrow \pi^+ \mu^+ \mu^-]$: $(5.0 \pm 0.4 \pm 0.9) \times 10^{-8}$ by BNL E787 [8], $(9.22 \pm 0.60 \pm 0.49) \times 10^{-8}$ by BNL E865 [9], and $(9.8 \pm 1.0 \pm 0.5) \times 10^{-8}$ by Fermilab HyperCP [10]. This mode is long distance dominated but of considerable value in constraining chiral perturbation theory models.

The purely leptonic channels appear to be completely dominated by the long distance two photon diagram. The only other observable is the final state lepton polarization which is unlikely to contain important physics given the saturated unitarity bound. The semi-leptonic $K \rightarrow \pi l^+ l^-$ measurements are approaching the Standard Model predictions where these 3 body modes should be observed. NA48/1 will help measure the CP conserving amplitudes. The theoretical problem of disentangling the long and short distance contributions look formidable (to me). None of the new experiments plan to

measure these modes in K_L^0 . Perhaps the experiments planned for the JHF will go after these important measurements.

$$K \rightarrow \pi \nu \bar{\nu}$$

The $K \rightarrow \pi \nu \bar{\nu}$ decays are where the precious metals live in FCNC kaon decays. The $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay is the *golden mode* which directly measures η , the imaginary part of V_{td} with negligible theoretical uncertainty; $\text{Br}[K_L \rightarrow \pi^0 \nu \bar{\nu}] = 1.8 \times 10^{-11} A^4 X(x_t)^2 \eta^2$. The challenge is that the Standard Model prediction is $\text{Br}[K_L \rightarrow \pi^0 \nu \bar{\nu}] = (2.6 \pm 1.2) \times 10^{-11}$ where the uncertainty comes from the present knowledge of the top quark mass and V_{cb} . The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay is the *silver mode*. It's rate is proportional to $|V_{td}|^2$ but with a significant correction for loops with a charmed quark; $\text{Br}[K^+ \rightarrow \pi^+ \nu \bar{\nu}] = 4.11 \times 10^{-11} A^4 X(x_t)^2 [(\rho - \rho_0)^2 + \eta^2]$. This correction depends on the poorly known charmed quark mass which gives rise to a theoretical uncertainty of $\sim 7\%$ in the latest NLO QCD analysis. The Standard Model prediction today is: $\text{Br}[K_L \rightarrow \pi^0 \nu \bar{\nu}] = (7.5 \pm 2.9) \times 10^{-11}$ [11]. This mode is *the* best place to directly measure $|\lambda_t| = |V_{ts}^* V_{td}|$.

On the experimental side there has been much activity and recent progress in searching for these ultra-rare decay modes. The KTeV experiment has reported two upper limits for $\text{Br}[K_L \rightarrow \pi^0 \nu \bar{\nu}]$; 1.6×10^{-6} [12] in a measurement where the only thing observed are 2 photons from a high P_t π^0 decay and 5.9×10^{-7} [13] where the π^0 Dalitz decay is observed. The former measurement is background limited, the latter is essentially background free. These limits are still 4-5 orders of magnitude above the Standard Model prediction.

The BNL E787 experiment has reported a major milestone in the progress toward measuring these modes with the report of a clean 2 event signal for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ [14] [15]. The second of these events and their final sensitivity plot are shown in Fig. 3. The experiment is done with stopped kaons where the entire $K^+ \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain is observed with precision measurements of π^+ energy, momentum and range.

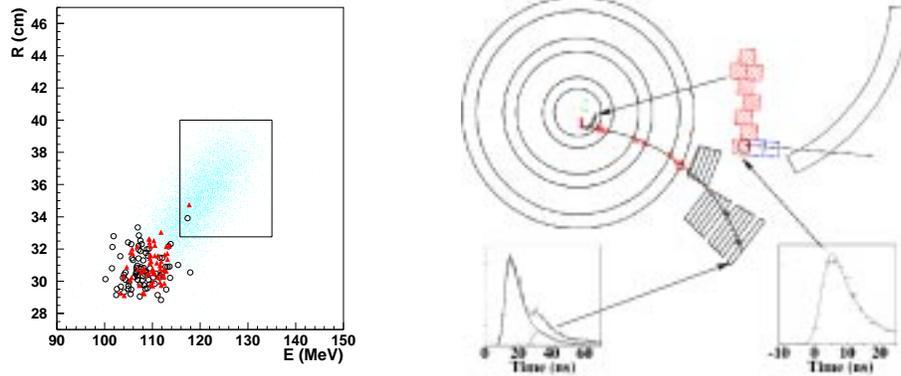


FIGURE 3. E787 - a) signal for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ b) the new event.

The branching ratio reported by E787 is $\text{Br}[K^+ \rightarrow \pi^+ \nu \bar{\nu}] = (1.58_{-0.81}^{+1.80}) \times 10^{-10}$ [15], about twice the Standard Model prediction but well within the uncertainty of a two event signal. The probability that both of these events are background is only $\sim 0.02\%$.

There are 4 recently approved new efforts in the $K \rightarrow \pi\nu\bar{\nu}$ sector. In $K^+ \rightarrow \pi^+\nu\bar{\nu}$ the BNL E787 collaboration was approved for another major run with an upgraded detector, as E949 [16]. This experiment, which I and several of my Fermilab and IHEP colleagues have joined, has a goal of a 5-10 events signal for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. Our data taking run resumes in February 2002. As the next step in $K^+ \rightarrow \pi^+\nu\bar{\nu}$ My colleagues and I, including several BNL members of E949, have been approved for a new Fermilab experiment, CKM (E921) [17], to measure the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ branching ratio with 100 events and less than 10% background using a decay in flight technique in a new Superconducting RF separated K^+ beam at 22 GeV/c. The CKM apparatus and expected signal are shown in Fig. 4.

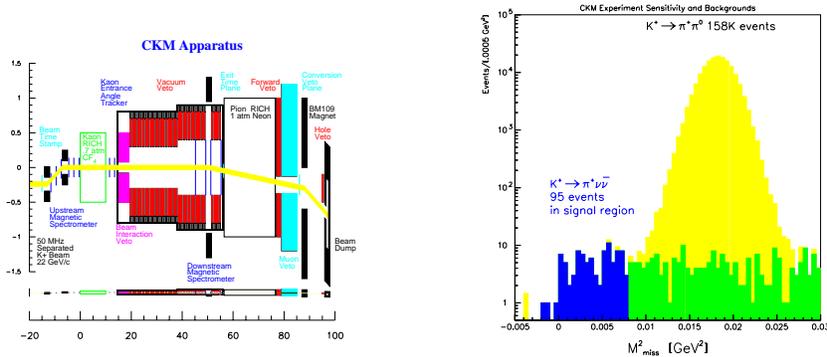


FIGURE 4. CKM - a) Apparatus and b) signal for $K^+ \rightarrow \pi^+\nu\bar{\nu}$.

There are two new experiments attempting to observe and measure the rate of $K_L \rightarrow \pi^0\nu\bar{\nu}$. E391a [18] at KEK has a goal of reaching the 1 event level with a hermetic photon calorimeter as a π^0 spectrometer and photon veto. They plan to start data taking in fall 2003. KOPIO [19] is a major new effort at BNL based on an innovative beam technique with a low momentum neutral beam (800 MeV/c) and time-of-flight to measure the K_L^0 momentum. Their goal is a 50 event signal with $S/N > 2$. Both these experiments require outstanding performance from their photon detector systems.

Successful measurements from these experiments, together with B sector results, will allow a direct test of the Standard Model hypothesis that the only source of CP violation is from η , the imaginary part of V_{td} . These measurements are all theoretically robust enough that a disagreement among them would require sources of CP violation beyond the Standard Model.

There are four such observables; two and the kaon system and 2 in the B systems. The sensitivities expected from these measurements are shown in Fig. 5. on the unitarity triangle plane. If these four measurements are not all consistent with a single point for the apex of the unitarity triangle then the Standard Model description of the source of CP violation is, at least, incomplete.

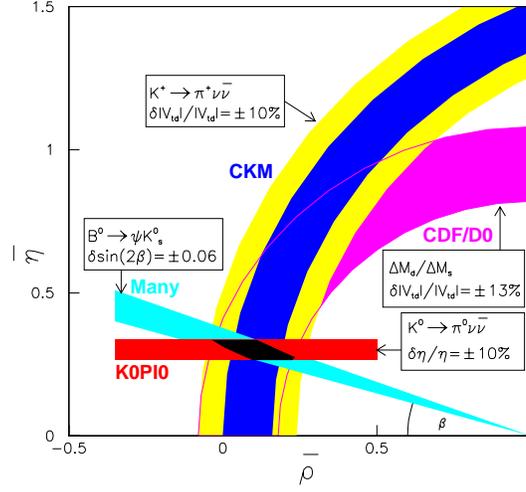


FIGURE 5. Unitary triangle with expected sensitivities from theoretically clean measurements.

CP/T VIOLATION

The increased sensitivity of recent experiments have now permitted the measurement of new CP or T violating observables in K_L^0 decays. The radiative decay $K_L \rightarrow \pi^+ \pi^- \gamma$ which has both CP conserving direct photon emission (DE) and CP violating internal bremsstrahlung (IB) amplitudes. KTeV has measured both the rate, $\text{Br}[K_L \rightarrow \pi^+ \pi^- \gamma, E_\gamma^* > 20 \text{MeV}] = 4.28 \times 10^{-5}$ and the relative fraction $DE/(DE + IB) = 0.683 \pm 0.011$ [20] which is a CP violating effect in the interference of the DE and IB amplitudes. In $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ decay this same interference manifests itself as an asymmetric azimuthal angular correlation between the the $\pi^+ \pi^+$ and $e^+ e^-$ decay planes. KTeV has measured both the rate; $\text{Br}[K_L \rightarrow \pi^+ \pi^- e^+ e^-] = (3.6 \pm 0.6 \pm 0.4) \times 10^{-7}$ [21] and CP (and T) violating asymmetry; $0.136 \pm 0.025 \pm 0.012$ [22]. This is the largest CP violating effect ever seen. In a preliminary result [23], NA48 has reported a measurement of this same asymmetry in $K_S \rightarrow \pi^+ \pi^- e^+ e^-$ where there is no CP violation. They report $\text{Br}[K_S \rightarrow \pi^+ \pi^- e^+ e^-] = (4.3 \pm 0.2 \pm 0.3) \times 10^{-5}$ and $A = -0.002 \pm 0.034 \pm 0.012$, consistent with zero as expected. KTeV has also just recently reported [24] a new measurement of the charge asymmetry in $K_L \rightarrow \pi^\pm e^\mp \nu$ decay. Their new value, $\delta_L = (3322 \pm 58 \pm 46) \times 10^{-6}$ is in good agreement with previous measurements and 2.4 times more precise than the best prior result.

At KEK E246 is re-measuring the transverse μ^+ polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay. This is a T odd observable. They report $P_T = -0.0033 \pm 0.0037 \pm 0.0009$ [25] and expect to achieve a final uncertainty of $\sigma(P_T) = 0.0030$ when all their data is analyzed. E246 has also made new measurements of the form factors in $K^+ \rightarrow \pi^0 e^+ \nu$ decay. They report [26] results consistent with zero for both the scalar $[|f_S/f_+| = -0.002 \pm 0.026 \pm 0.014]$ and tensor $[|f_T/f_+| = -0.01 \pm 0.14 \pm 0.09]$ form-factors contradicting the the 3σ non-zero effects in the current PDG averages.

Direct CP violation is now well established in the neutral kaon system with the recent results from KTeV and NA48. The connections between ϵ and ϵ'/ϵ and Standard Model parameters are still seriously limited by theoretical uncertainties. The $K_L \rightarrow \pi^+\pi^-e^+e^-$ asymmetry measurement is one of the most beautiful results I've seen in years. This asymmetry and the charge asymmetry in $K^+ \rightarrow \pi^0e^+\nu$ are due to indirect CP violation, like ϵ , so they suffer similar theoretical difficulties. The studies of Kaon semi-leptonic decays are beginning to achieve the levels of sensitivity and precision to the details of the electro-weak interaction we normally associate only with muon decay.

LEPTON FLAVOR VIOLATION

The search for lepton flavor violation (LFV) has been a topic of enduring interest. With the recent evidence for neutrino oscillations indicating that lepton flavor is not conserved this topic has become even hotter. In the kaon system LFV has usually been parameterized by positing a new flavor changing neutral current decaying to $\mu^\pm e^\mp$ which has full Fermi weak couplings and is suppressed only by its large mass in the propagator. By dimensional analysis a branching ratio limit of 10^{-12} corresponds to a lower mass limit on this LFV current of $\sim 1000M_W$ or $\sim 82TeV$.

In the kaon system this has led to new searches for the LFV modes; $K_L \rightarrow \pi^0\mu^\pm e^\mp$, $K^+ \rightarrow \pi^+\mu^+e^-$, and $K_L \rightarrow \mu^\pm e^\mp$. BNL E871 has reported $\text{Br}[K_L \rightarrow \mu^\pm e^\mp] < 4.7 \times 10^{-12}$ [3] in a background free measurement, as mentioned above. KTeV has a preliminary upper limit for $K_L \rightarrow \pi^0\mu^\pm e^\mp$; $\text{Br}[K_L \rightarrow \pi^0\mu^\pm e^\mp] < 4.4 \times 10^{-10}$ [27] with 2 events observed. BNL E865 has reported their final limit on $K^+ \rightarrow \pi^+\mu^+e^-$; $\text{Br}[K^+ \rightarrow \pi^+\mu^+e^-] < 2.8 \times 10^{-11}$ [28] BNL E865 also has a new limit on "neutrino-less double μ decay": $\text{Br}[K^+ \rightarrow \mu^+\mu^+\pi^-] < 3.0 \times 10^{-9}$ [29].

Lepton flavor violation is a topic with so little theoretical guidance that there are no clear "goal posts". If the only source of LFV is mixing in the neutrino sector then the LFV effects induced in the kaon sector are unobservably small ($\sim 10^{-25}$). Technicolor, Leptoquark and compositeness models might apply, each with their own parameters and predictions for observable effects in the quark, charged lepton and neutrino sectors. This field has been driven by better experimental ideas. The present state of the art in the kaon sector has been established by BNL E871, BNL E865 and KTeV. In the immediate future the new searches will be back in the charged lepton sector with the search for $\mu^+Z \rightarrow e^+Z$ in the new MECO experiment at BNL and new searches for $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-$ at PSI. Further progress in the kaon sector awaits some new experimental ideas.

SUMMARY

The kaon sector continues to be a gold mine 55 years after the discovery of the kaon. I've reviewed here 23 recent results from 8 different experiments (BNL787, BNL865, BNL871, NA48, KTeV/FNAL799, KTeV/FNAL832, HyperCP/FNAL871 and KEK246) from 4 laboratories on 3 continents. This is far from a complete review

of recent work. Good progress is being made on understanding the sources of CP violation with FCNC and other decays. The searches for lepton flavor violation have achieved substantially improved limits; sufficient to mute the discussions of whole classes of formerly fashionable models.

The next round of experiments are underway with a new experiment or two at each of the labs. The main theme of these measurements is a direct confrontation of the Standard Model's description of the source of matter - anti-matter asymmetry in nature. We're not done learning from the kaon system yet.

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