Rare Kaon Decays: Progress and Prospects

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1 Introduction

There is a large overlap in the current physics motivation for investigating B-meson and K-meson decays. The much newer and heavier b quark opens many possibilities for studying interesting decay channels with fascinating phenomenologies of mixing, oscillations, and CP violation. In the past year the promise of revealing the origin of CP violation has begun to be realized in pioneering experimental studies at e^+e^- colliders. The asymmetries observed in $B \to \Psi K_S$ decays by BABAR and BELLE provide the first conclusive evidence for CP violation outside the neutral K system.

K decays, a much older game, have long been a gold mine of surprising information at the forefront of particle physics. K decay experiments opened the doors to quark mixing and CP violation. In the intervening years, the effort to establish consistency with the Standard Model (SM) description involving direct CP violation was a protracted battle. Nevertheless, KTEV[1] and NA48[2] finally agreed on evidence for direct CP violation through consistent non-zero values of ϵ'/ϵ in $K \to \pi\pi$ decays. However, as with many approaches to CP violation involving K and B decays, the underlying short distance physics is not easy to get at due to complications associated with strong interactions including penguin diagram processes.

The CP-violating asymmetry in $B \to \Psi K_S$ decays which determines $sin(2\beta)$, and the ratio of B_s/B_d mixing (x_s/x_d) which yields $|\frac{V_{ts}}{V_{td}}|$ stand out as theoretically unambiguous quantities, relatively free from strong interaction uncertainties. Together they can cleanly determine the apex of the usual unitary triangle giving a powerful test of the consistency of the SM. $sin(2\beta)$ is becoming known to increasing precision as discussed at this conference and there is optimism that B_s mixing will be measured in Run II at the Tevatron, although extracting $|V_{td}|$ is subject to some uncertainty due to SU(3)-breaking effects.

During the past few years the state-of-the-art in rare K decays has reached single event sensitivities of 10^{-12} in experiments at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS). BNL E871 reported 6200 events of $K_L^0 \to \mu^+\mu^-$ decay at the 10^{-8} level[3] and 4 events of $K_L^0 \to e^+e^-$ at 10^{-11}[4]. Two events were observed by BNL E787 with the kinematically incomplete $K^+ \to \pi^+ \nu\overline{\nu}$ signature at the 10^{-10} level[5]. These successes have opened up the possibility of fully accessing the "dynamic duo" of $K^+ \to \pi^+ \nu\overline{\nu}$ and $K^0_L \to \pi^0 \nu\overline{\nu}$ which offer the best possibilities for obtaining high quality information on short distance physics, complementary and comparable in precision to the leading approaches using B mesons.

The observation of $K^+ \to \pi^+ \nu\overline{\nu}$ by E787 is consistent with the SM expectation. To fully explore the possibility of new physics or to make a precise measurement of the t-d quark coupling $|V_{td}|$, a new measurement has just commenced. E949 at the BNL AGS is designed to obtain sensitivity an order of magnitude below the SM prediction. Later in the decade, the CKM experiment[6] at Fermilab will begin to pursue $K^+ \to \pi^+ \nu\overline{\nu}$ at even higher precision.

The K sector can also yield the single most incisive measurement in the study of CP violation through a measurement of the branching ratio for $K^0_L \to \pi^0 \nu\overline{\nu}$ decay. Within the SM context, this is a unique quantity which directly measures the area of the CKM unitarity triangles *i.e.* the physical parameter that characterizes all CP violation phenomena, or the height of the triangle shown in Fig. 1. The quest to observe $K^0_L \to \pi^0 \nu\overline{\nu}$ is beginning in earnest with a pilot experiment at KEK (E391A) and the new KOPIO experiment at BNL. The measurements of $B(K^+ \to \pi^+ \nu\overline{\nu})$ and $B(K^0_L \to \pi^0 \nu\overline{\nu})$ will result in a complete picture of SM CP violation in the K system and a comparison with comparably precise measurements anticipated from the B sector will be possible.

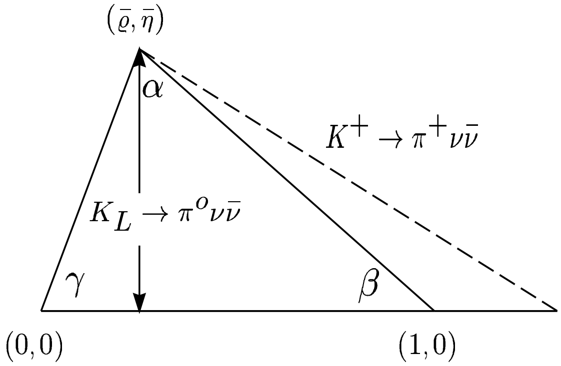

Figure 1: The unitarity triangle.

Other areas of current activity in the field of rare K decays include studies of radiative processes relevant to Chiral Perturbation Theory (CHPT) and searches for exotic reactions.

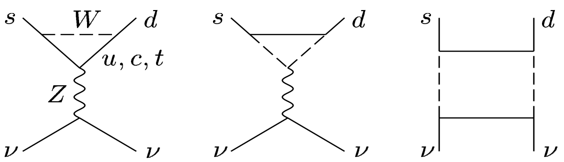

Figure 2: The leading electroweak diagrams inducing $K \rightarrow \pi\nu\overline{\nu}$ decays. For $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ only the top quark contributes.

2 THEORY OF $K \rightarrow \pi\nu\overline{\nu}$

While clean extraction of SM parameters from K decay observables like ϵ'/ϵ is presently precluded due to non-perturbative strong interaction uncertainties, $K^+ \rightarrow \pi^+\nu\overline{\nu}$ and $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ do not suffer from these maladies. In $K^+ \rightarrow \pi^+\nu\overline{\nu}$ and $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ decays, which arise at the one loop level in the SM as shown in Fig. 2, hadronic effects are well known from measurements of the similar decays K$\rightarrow \pi e\nu$ related by isospin[7]. The presence of the top quark in the loops makes these decays very sensitive to V_{td} [8] and the simple final states allow unusually precise calculations to be made. Small QCD corrections have been calculated to next-to-leading-logarithmic order [9]. Long distance effects are negligible in comparison with short distance effects. $K^+ \rightarrow \pi^+\nu\overline{\nu}$ is expected to occur with a branching ratio of $0.72 \pm 0.21 \times 10^{-10}$[10] with a purely theoretical uncertainty of about 7% due to a charm quark contribution to the loops.

$K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ decay is unique in that it is completely dominated by direct CP violation [11]. Since K_L^0 is predominantly a coherent, CP odd superposition of K^0 and $\overline{K}^0$, only the imaginary part of $V_{ts}^* V_{td}$ survives in the amplitude. The lack of a significant charm quark contribution reduces the intrinsic theoretical uncertainty to $\mathcal{O}(2\%)$. Since the value of the sine of the Cabibbo angle is well known, $Im(V_{ts}^* V_{td})$ is equivalent to the Jarlskog invariant, $\mathcal{J} \equiv -Im(V_{ts}^* V_{td} V_{us}^* V_{ud}) = -\lambda(1-\frac{\lambda^2}{2}) Im(V_{ts}^* V_{td})$. $\mathcal{J}$ is equal to twice the area of any of the six possible unitarity triangles [12]. Since theoretical uncertainties are extremely small, measurement of $B(K_L^0 \rightarrow \pi^0\nu\overline{\nu})$ will provide the standard against which all other measures of CP violation will be compared, and even small deviations from the expectation derived from SM predictions or from other measurements, *e.g.* in the B sector, will unambiguously signal the presence of new physics. In the SM context the branching ratio for $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ is given by[13]

$$B(K_L^0 \rightarrow \pi^0\nu\overline{\nu}) = 1.8 \cdot 10^{-10} (\frac{Im(V_{ts}^* V_{td})}{\lambda^5})^2 X^2(x_t) = 1.8 \cdot 10^{-10} \eta^2 A^4 X^2(x_t), \qquad (1)$$

where $X(x_t)$ is a kinematic function of the top quark mass. The branching ratio for $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ is expected to lie in the range $(2.6 \pm 1.2) \cdot 10^{-11}$. A clean measure of the height of the unitary triangle, η, is provided by the $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ branching ratio. All other parameters being known, Eq. 1 implies that the relative error of η is half that of a measurement of $B(K_L^0 \to \pi^0 \nu\overline{\nu})$. Thus, for example, a 15% measurement of $B(K_L^0 \to \pi^0 \nu\overline{\nu})$ can, in principle, determine η to 7.5%.

Most forms of new physics [14, 15, 10] postulated to augment or supersede the SM have implications for $\mathrm{B}(K \to \pi\nu\overline{\nu})$. In minimal supersymmetry and in some multi-Higgs doublet models [16], the extraction of $\sin 2\alpha$ and $\sin 2\beta$ from CP asymmetries in B decays would be unaffected. Such effects might then show up in a comparison with $K_L^0 \to \pi^0 \nu\overline{\nu}$, where, e.g., charged Higgs contributions modify the top quark dependent function in $B(K_L^0 \to \pi^0 \nu\overline{\nu})$. In other new physics scenarios, such as supersymmetric flavor models [17], the effects in $K \to \pi\nu\overline{\nu}$ tend to be small, while there can be large effects in the B (and also the D) system. In these models the rare K decays are the only clean way to measure the true CKM parameters. Examples of new physics scenarios that show large deviations from the SM in $K \to \pi\nu\overline{\nu}$ are provided by some extended Higgs models, in topcolor-assisted technicolor models [18], in left-right symmetric models [19], in models with extra quarks in vector-like representations [15], lepto-quark exchange [15], and in 4-generation models [20]. The confirmation of a relatively large value for ϵ'/ϵ has focussed attention on the contributions of flavor-changing Z-penguin diagrams in generic low-energy supersymmetric extensions of the SM [13]. Such diagrams can interfere with the weak penguins of the SM, and either raise or reduce the predicted $B(K_L^0 \to \pi^0 \nu\overline{\nu})$ by considerable factors. The effects of SUSY and other non-SM approaches on the K and B system generally turn out to be different and apparent discrepancies between measurements of SM quantities would be indications of new physics.

3 Measurement of $K^+ \to \pi^+ \nu\overline{\nu}$

The final results from BNL E787 reported recently[5] were based on observations of decays of 5.9×10^{12} K mesons at rest. Measurement of the $K^+ \to \pi^+ \nu\overline{\nu}$ decay involves only the π^+ track and π^+ decay products and was accomplished with an efficiency of 2×10^{-3}. The efficiency is relatively small because of the necessity to suppress similar background processes by up to 10 orders of magnitude. Major background sources include the two-body decays $K^+ \to \mu^+ \nu_\mu$ and $K^+ \to \pi^+ \pi^0$, pions scattered from the beam, and K^+ charge exchange (CEX) reactions resulting in decays $K_L^0 \to \pi^+ l^- \overline{\nu}_l$, where $l = e$ or μ. In order to make an unambiguous measurement of $B(K^+ \to \pi^+ \nu\overline{\nu})$, the sum of all backgrounds was suppressed to the estimated level of $0.15^{+0.05}_{-0.04}$ events. The background suppression procedures and estimates were subjected to extensive verification, and a signal-to-background function was created to evaluate potential $K^+ \to \pi^+ \nu\overline{\nu}$ candidates.

The combined result for E787 data taken between 1995 and 1998 is shown in Fig. 3, the range vs. kinetic energy of events surviving all other cuts. In Fig. 3 the box represents the signal region in which two events appear. A likelihood ratio

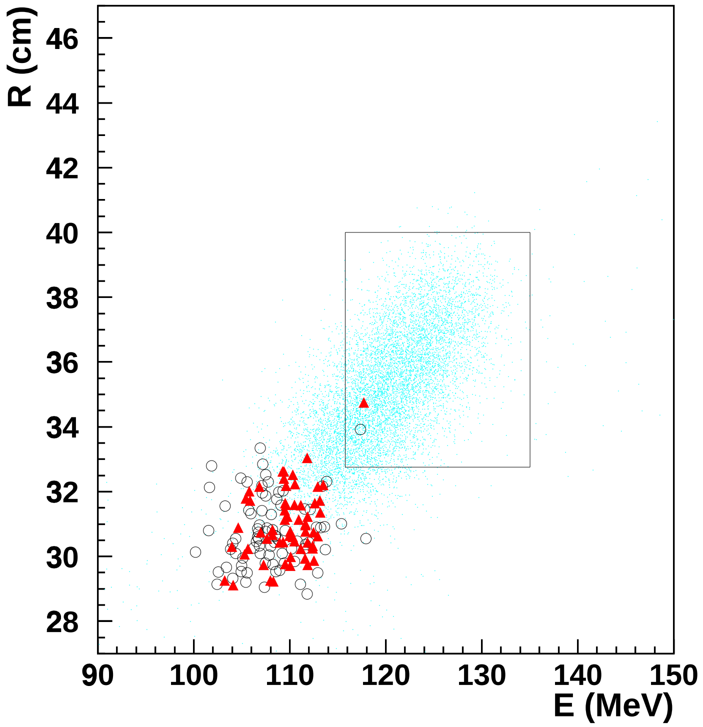

Figure 3: Range vs. energy plot of the E787 final sample for $K^+ \to \pi^+ \nu \overline{\nu}$. The circles are for the 1998 data and the triangles are for the 1995-97 data set. The group of events around $E = 108$ MeV is due to the $K^+ \to \pi^+ \pi^0$ background. The simulated distribution of expected events from $K^+ \to \pi^+ \nu \overline{\nu}$ is indicated by dots.

technique[21] was used to determine the best estimate of the branching ratio. Based on two observed events and the expected background levels, the result is $B(K^+ \to \pi^+ \nu \overline{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$. This result is consistent with the SM prediction. The estimated probability for the observation to be due entirely to background is at the level of 0.02% [21]. D'Ambrosio and Isidori[10] have illustrated the impact of the current E787 results on the measurements of SM quark mixing and CP violation parameters and discussed the possibilities for identifying new physics.

The follow-on experiment E949 is an improved version of E787. Upgrades included enhancements to the photon detection system, and improvements to the DAQ system, beam counters, tracking chamber electronics, monitoring systems, among others. E949 is aiming for a single event sensitivity of approximately 10^{-11}, an order of magnitude below the SM level. It began data-taking in early 2002.

In the longer term future, the proposed CKM experiment[6] at Fermilab shown schematically in fig. 4 seeks another order of magnitude in sensitivity, i.e. 10^{-12}.

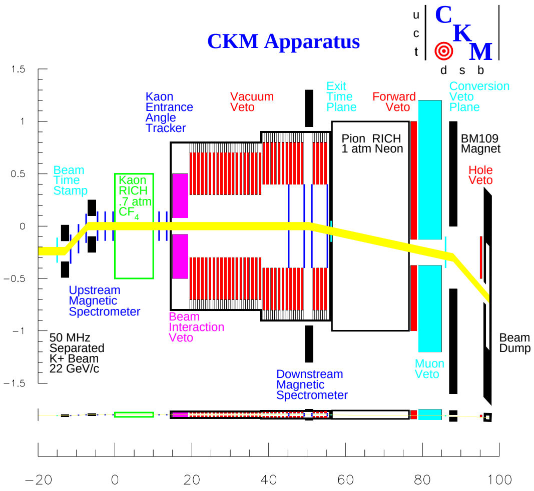

Figure 4: Layout of the proposed CKM experiment at Fermilab.

CKM uses particle identification based on ring imaging Cerenkov detectors along with momentum measurements to suppress backgrounds. At the SM level, a signal of approximately 95 events with a signal/noise ratio $S/N = 7$ is sought.

4 Prospects for Measuring $K_L^0 \to \pi^0 \nu \overline{\nu}$

The experimental challenges of studying $\mathrm{B}(K_L^0 \to \pi^0 \nu \overline{\nu})$ are comparable to those encountered in the measurement of $K^+ \to \pi^+ \nu \overline{\nu}$. There are similar competing decays, particularly $K_L^0 \to \pi^0 \pi^0$, that also yield π^0s but with branching ratios that are millions of times larger. Interactions between neutrons and kaons in the neutral beam with residual gas in the decay volume can also result in emission of single π^0s, as can the decays of hyperons which might occur in the decay region. The current experimental limit $B(K_L^0 \to \pi^0 \nu \overline{\nu}) < 5.9 \times 10^{-7}$ [22] was a by-product of the KTeV experiment at Fermilab.

To definitively measure $K_L^0 \to \pi^0 \nu \overline{\nu}$, a detection technique must be developed that provides maximum possible redundancy for this kinematically unconstrained decay, that has an optimum system for insuring that the observed π^0 is the only detectable particle emanating from the K_L^0 decay, and that has multiple handles for identifying possible small backgrounds that might simulate the desired mode.

A first step at a dedicated search for $K_L^0 \to \pi^0 \nu \overline{\nu}$ is commencing soon at KEK with experiment E391a which aims for a sensitivity of $10^{-10} - 10^{-9}$. This experiment uses a narrowly collimated “pencil” neutral beam[23] along with a high acceptance hermetic detector. E391a will test the limits of reliance on photon detection efficiency to suppress the major backgrounds and may lead to a proposal at the emerging Japanese Hadron Facility.

The new KOPIO experiment at BNL is scoped to reach a sensitivity more than an order of magnitude below the SM prediction, i.e. 10^{-12}, aiming for at least 50 events of $K^0_L \to \pi^0 \nu \overline{\nu}$ with $S/N > 2$. KOPIO, which is presently in the R&D and design phase, employs a low momentum time-structured K^0_L beam to allow determination of the incident kaon momentum by time-of-flight. This intense beam, with its special characteristics, can be provided by the BNL AGS. Utilizing low momentum also permits a detection system for the π^0 decay photons that yields a fully constrained reconstruction of the π^0's mass, energy, and, momentum. The system for vetoing extra particles is well understood. These features which are similar to those employed successfully in the E787 measurement of $K^+ \to \pi^+ \nu \overline{\nu}$ provide the necessary redundancy and checks.

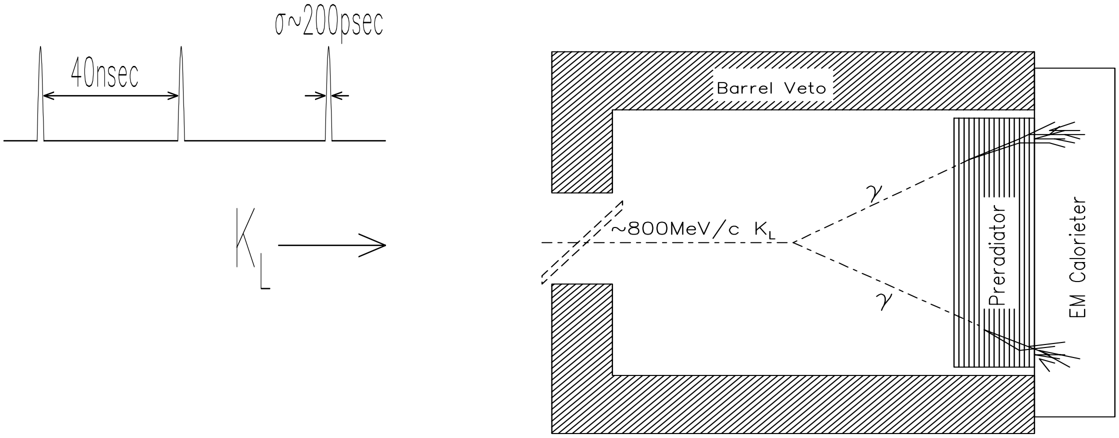

Figure 5: Elements of the KOPIO concept : a pulsed primary beam produces low energy kaons whose time-of-flight reveals their momentum when the π^0 from $K^0_L \to \pi^0 \nu \overline{\nu}$ decay is reconstructed.

Figure 5 shows a simplified representation of the beam and detector concept for KOPIO. Photons from $K^0_L \to \pi^0 \nu \overline{\nu}$ decay are observed in a two-stage endcap detector comprised of a fine-grained preradiator with angular resolution approximately 25 mr for photons of 250 MeV. It is followed by a shashlyk-type electromagnetic calorimeter. The preradiator-calorimeter combination is expected to have an energy resolution of $\sigma_{\mathrm{E}}/\mathrm{E} < 0.03/\sqrt{\mathrm{E(GeV)}}$. The entire decay region is surrounded by efficient charged particle and photon detectors.

5 Other Rare K Decays

Considering the obvious difficulty of measuring $K^0_L{\to}\pi^0\nu\overline{\nu}$ there is still interest in studying $K^0_L \to \pi^0 e^+e^-$ to obtain information on direct CP violation. However this decay presents formidable experimental and theoretical challenges. The direct CP-violating component which is due to diagrams similar to those for $K^0_L{\to}\pi^0\nu\overline{\nu}$ is estimated to occur at a branching ratio of 4×10^{-12}. There are potentially important competing effects from CP-conserving amplitudes, CP-violating amplitudes due to mixing, and backgrounds from similar decay signatures like $K^0_L \to \gamma\gamma e^+e^-$[24].

The present limit is $\mathrm{B}(K^0_L \to \pi^0 e^+e^-) < 5.1 \times 10^{-10}$[25]. The NA48 collaboration has recently reported a result on the branching ratio and shape of the spectrum for $K^0_L \to \pi^0\gamma\gamma$ which can be used to limit the CP-conserving component of $K^0_L \to \pi^0 e^+e^-$[26]. A total of 2558 $K^0_L \to \pi^0\gamma\gamma$ events were observed with a background estimated to be 3.2% giving the results $\mathrm{B}(K^0_L \to \pi^0\gamma\gamma) = 1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm} \times 10^{-6}$ and the vector coupling constant $a_v = -0.46 \pm 0.03_{stat} \pm 0.04_{syst}$. [1] Using these results and a limit on the rate in the region $m_{\gamma\gamma} < m_{\pi^0}$, NA48 presented an estimate for the CP-conserving component of $\mathrm{B}(K^0_L \to \pi^0 e^+e^-)_{CPC} = 4.7^{+2.2}_{-1.8} \times 10^{-13}$, suggesting that it may not dominate in the measurement of CP-violating effects in $K^0_L \to \pi^0 e^+e^-$. However, there is also a dispersive amplitude which is not reliably calculated which could be of comparable importance[24].

The NA48 experiment has now been upgraded to NA48/1[28]. Improvements made to the detectors and beam lines will enable experiments with 100x (or greater) intensities to achieve single event sensitivities to rare decays at the 10^{-10} level. NA48/1 plans to study many processes including $K^0_S \to \pi^0 l^+l^-$ (which can be used to limit the contribution to indirect CP violation in $K^0_L \to \pi^0 e^+e^-$), $K^0_S \to 3\pi$, and time-dependent CP-violating effects in $K^0_{L,S} \to \pi\pi\gamma^*$ decays. In addition, semi-leptonic and radiative neutral hyperon decays will be investigated.

6 Summary and Prospects

Rare kaon decay experiments underway or planned for the BNL AGS, Fermilab and KEK aim to study the extraordinary decays $K^+{\to}\pi^+\nu\overline{\nu}$ and $K^0_L{\to}\pi^0\nu\overline{\nu}$. BNL E787 has presented evidence for $K^+{\to}\pi^+\nu\overline{\nu}$ at the 10^{-10} level based on the observation of two clean events leading the way for BNL E949 and CKM at Fermilab which seek one and two orders of magnitude greater sensitivities. The proposed KOPIO measurement of $B(K^0_L{\to}\pi^0\nu\overline{\nu})$ will allow a determination of the imaginary part of $V^*_{ts}V_{td}$ giving the fundamental CP-violating parameter of the SM, in a uniquely clean manner. Since the measurement of $B(K^+{\to}\pi^+\nu\overline{\nu})$ determines $|V^*_{ts}V_{td}|$, a complete derivation of the

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[1] Comparable measurements reported by the KTEV collaboration[27] gave $\mathrm{B}(K^0_L \to \pi^0\gamma\gamma) = 1.68 \pm 0.10 \times 10^{-6}$ and $a_v = -0.72 \pm 0.05 \pm 0.06$.

unitarity triangle is facilitated. The parameters derived from the K decays will be compared to high precision data expected to come from the B sector allowing for incisive searches for new physics.

New results on several other rare K decays have recently become available from NA48 ($K_L^0 \to \pi^0\gamma\gamma$), the HYPER-CP collaboration ($K^\pm \to \pi^\pm\mu\mu$)[29] and KLOE at DAPHNE ($K_S^0 \to \pi e\nu$)[30] shedding light on issues in CP violation and Chiral Perturbation Theory (CHPT). Other new results on exotic processes have been presented recently by BNL E787 ($K^+ \to \pi^+ a$[31] and $K^+ \to \pi^+\gamma$[32]) and new results on lepton flavor violating decays and other processes are anticipated from E865 at BNL and KTEV/E799 at Fermilab.

At CERN and DAPHNE, additional rare radiative decays of K_L and K_S are being vigorously pursued along with many other studies relevant to tests of CP/CPT violation and CHPT by the upgraded NA48/1 experiment and by KLOE.

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