RARE KAON DECAYS

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A. Introduction: There are several useful reviews on rare kaon decays and related topics [1–14]. Activity in rare kaon decays can be divided roughly into four categories:

1. Searches for explicit violations of the Standard Model
2. Measurements of Standard Model parameters
3. Searches for CP violation
4. Studies of strong interactions at low energy.

The paradigm of Category 1 is the lepton flavor violating decay $K_L \to \mu e$. Category 2 includes processes such as $K^+ \to \pi^+\nu\overline{\nu}$, which is sensitive to $|V_{td}|$. Much of the interest in Category 3 is focused on the decays $K_L \to \pi^0\ell\overline{\ell}$, where $\ell \equiv e, \mu, \nu$. Category 4 includes reactions like $K^+ \to \pi^+\ell^+\ell^-$ which constitute a testing ground for the ideas of chiral perturbation theory. Category 4 also includes $K_L \to \pi^0\gamma\gamma$ and $K_L \to \ell^+\ell^-\gamma$. The former is important in understanding a CP-conserving contribution to $K_L \to \pi^0\ell^+\ell^-$, whereas the latter could shed light on long distance contributions to $K_L \to \mu^+\mu^-$.

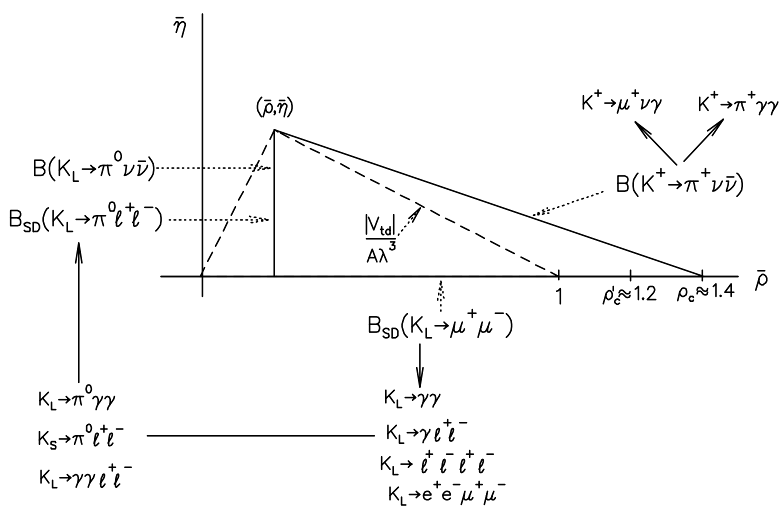

Figure 1: Role of rare kaon decays in determining the unitarity triangle. The solid arrows point to auxiliary modes needed to interpret the main results, or potential backgrounds to them.

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The interplay between Categories 2-4 can be illustrated in Fig. 1. The modes $K \to \pi\nu\overline{\nu}$ are the cleanest ones theoretically. They can provide accurate determinations of certain CKM parameters (shown in the figure). In combination with alternate determinations of these parameters they also constrain new interactions. The modes $K_L \to \pi^0 e^+ e^-$ and $K_L \to \mu^+\mu^-$ are also sensitive to CKM parameters. However, they suffer from a series of hadronic uncertainties that can be addressed, at least in part, through a systematic study of the additional modes indicated in the figure.

B. Explicit violations of the Standard Model: Much activity has focussed on searches for lepton flavor violation (LFV). This is motivated by the fact that many extensions of the minimal Standard Model violate lepton flavor and by the potential to access very high energy scales. For example, the tree-level exchange of a LFV vector boson of mass M_X that couples to left-handed fermions with electroweak strength and without mixing angles yields $\mathrm{B}(K_L \to \mu e) = 4.7 \times 10^{-12}(148\ \mathrm{TeV}/M_X)^4$ [5]. This simple dimensional analysis may be used to read from Table 1 that the reaction $K_L \to \mu e$ is already probing scales of over 100 TeV. Table 1 summarizes the present experimental situation vis a vis LFV. The decays $K_L \to \mu^\pm e^\mp$ and $K^+ \to \pi^+ e^\mp \mu^\pm$ (or $K_L \to \pi^0 e^\mp \mu^\pm$) provide complementary information on potential family number violating interactions since the former is sensitive to parity-odd couplings and the latter is sensitive to parity-even couplings. Limits on certain lepton-number violating kaon decays [15,16] also exist. Related searches in μ and τ processes are discussed in our section "Tests of Conservation Laws".

Table 1: Searches for lepton flavor violation in K decay

Mode	90% CL upper limit	Exp't	Yr./Ref.
$K^+ \to \pi^+ e^- \mu^+$	1.2×10^{-11}	BNL-865	2003/Ref. 17
$K^+ \to \pi^+ e^+ \mu^-$	5.2×10^{-10}	BNL-865	2001/Ref. 15
$K_L \to \mu e$	4.7×10^{-12}	BNL-871	1998/Ref. 18
$K_L \to \pi^0 e \mu$	3.4×10^{-10}	KTeV (prelim.)	2003/Ref. 19

Physics beyond the SM is also pursued through the search for $K^+ \to \pi^+ X^0$, where X^0 is a very light, noninteracting particle (*e.g.* hyperphoton, axion, familon, *etc.*). The 90% CL upper limit on this process is 5.9×10^{-11} [20].

C. Measurements of Standard Model parameters:

Until 1997, searches for $K^+ \to \pi^+ \nu\overline{\nu}$ were motivated by the possibility of observing non-SM physics because the sensitivity attained was far short of the SM prediction for this decay [21] and long-distance contributions are known to be quite small [2,22,23]. Since then, BNL-787 has observed two candidate events [20,24], and BNL-949 has observed one more, yielding a branching ratio of $(1.47^{+1.30}_{-0.89}) \times 10^{-10}$ [25]. At this level, this reaction becomes interesting from the point of view of constraining SM parameters. A new experiment with a sensitivity goal of $\sim 10^{-12}$/event was proposed [26] at CERN in 2005. In the future this mode may provide grounds for precision tests of the flavor structure of the Standard Model [27]. The branching ratio can be written in terms of the very well-measured K_{e3} rate as [2]:

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) = \frac{\alpha^2 \mathrm{B}(K^+ \to \pi^o e^+ \nu)}{V_{us}^2 2\pi^2 \sin^4 \theta_W} \times \sum_{l=e,\mu,\tau} |V_{cs}^* V_{cd} X_{NL}^{\ell} + V_{ts}^* V_{td} X(m_t)|^2 \qquad (1)$$

to eliminate the *a priori* unknown hadronic matrix element. Isospin breaking corrections to the ratio of matrix elements reduce this rate by 10% [28]. In Eq. (1) the Inami-Lim function $X(m_t)$ is of order 1 [29], and X_{NL}^{ℓ} is several hundred times smaller. This form exhibits the strong dependence of this branching ratio on $|V_{td}|$. QCD corrections, which mainly affect X_{NL}^{ℓ}, lead to a residual error of $< 5\%$ for the decay amplitude [12,23,30,31]. Evaluating the constants in Eq. (1), one can cast this result in terms of the CKM parameters λ, V_{cb}, $\bar{\rho}$ and $\bar{\eta}$ (see our Section on "The Cabibbo-Kobayashi-Maskawa mixing matrix") [12]

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) \approx 1.6 \times 10^{-5} |V_{cb}|^4 [\sigma \bar{\eta}^2 + (\rho_c - \bar{\rho})^2] \qquad (2)$$

where $\rho_c \equiv 1 + (\frac{2}{3}X^e_{NL} + \frac{1}{3}X^\tau_{NL})/(|V_{cb}|^2 X(m_t)) \approx 1.4$ and $\sigma \equiv 1/(1-\frac{1}{2}\lambda^2)^2$. Thus, $\mathrm{B}(K^+ \to \pi^+\nu\overline{\nu})$ determines an ellipse in the $\bar\rho$, $\bar\eta$ plane with center $(\rho_c, 0)$ and semiaxes $\approx \dfrac{1}{|V_{cb}|^2}\sqrt{\frac{\mathrm{B}(K^+\to\pi^+\nu\overline{\nu})}{1.6\times10^{-5}}}$ and $\dfrac{1}{\sigma|V_{cb}|^2}\sqrt{\frac{\mathrm{B}(K^+\to\pi^+\nu\overline{\nu})}{1.6\times10^{-5}}}$. Current constraints on the CKM parameters lead to a predicted branching ratio $(8.0\pm1.1)\times10^{-11}$ [31], near the lower end of the BNL-787 measurement.

The decay $K_L \to \mu^+\mu^-$ also has a short distance contribution sensitive to the CKM parameter $\bar\rho$, given by [12]:

$$\mathrm{B_{SD}}(K_L \to \mu^+\mu^-) \approx 2.7\times10^{-4}|V_{cb}|^4(\rho'_c - \bar\rho)^2 \tag{3}$$

where ρ'_c depends on the charm quark mass and is approximately 1.2. This decay, however, is dominated by a long-distance contribution from a two-photon intermediate state. The absorptive (imaginary) part of the long-distance component is determined by the measured rate for $K_L \to \gamma\gamma$ to be $\mathrm{B_{abs}}(K_L \to \mu^+\mu^-) = (6.64\pm0.07)\times10^{-9}$; and it almost completely saturates the observed rate $\mathrm{B}(K_L \to \mu^+\mu^-) = (6.87\pm0.11)\times10^{-9}$ [32]. The difference between the observed rate and the absorptive component can be attributed to the (coherent) sum of the short-distance amplitude and the real part of the long-distance amplitude. The latter cannot be derived directly from experiment [33] but can be estimated with certain assumptions [34,35]. The decay $K_L \to e^+e^-$ is completely dominated by long distance physics and is easier to estimate. The result, $B(K_L \to e^+e^-) \sim 9\times10^{-12}$ [33,36], is in good agreement with the BNL-871 measurement, $(8.7^{+5.7}_{-4.1})\times10^{-12}$ [37].

D. Searches for direct CP violation: The mode $K_L \to \pi^0\nu\overline{\nu}$ is dominantly CP-violating and free of hadronic uncertainties [2,38,39]. In the Standard Model this mode is dominated by an intermediate top-quark state and does not suffer from the small uncertainty associated with the charm-quark intermediate state that affects the mode $K^+ \to \pi^+\nu\overline{\nu}$. The branching ratio is given approximately by Ref. 12:

$$\mathrm{B}(K_L \to \pi^0\nu\overline{\nu}) \approx 7.6\times10^{-5}|V_{cb}|^4\bar\eta^2 \ . \tag{4}$$

With current constraints on the CKM parameters this leads to a predicted branching ratio $(3.0 \pm 0.6) \times 10^{-11}$ [40]. The current published experimental upper bound is $\mathrm{B}(K_L \to \pi^0 \nu \overline{\nu}) \leq 5.9 \times 10^{-7}$ [41]. The 90% CL bound on $K^+ \to \pi^+ \nu \bar{\nu}$ provides a nearly model independent bound $B(K_L \to \pi^0 \nu \bar{\nu}) < 1.4 \times 10^{-9}$ [42]. KEK-391a [43], which began data-taking in early 2004, aims to reach this level, and has presented a preliminary result of $\mathrm{B}(K_L \to \pi^0 \nu \overline{\nu}) \leq 2.86 \times 10^{-7}$ [44]. A Letter of Intent for an experiment to reach the $\sim 5 \times 10^{-13}$/event level has been submitted to the J-PARC PAC [45].

There has been much theoretical work on possible contributions to rare K decays beyond the SM. While in the simplest case of the MSSM with no new sources of flavor or CP violation the main effect is a suppression of the rare K decays [2,21,46], substantial enhancements are possible in more general SUSY models [47]. A comprehensive discussion can be found in Refs. [40] and [48].

The decay $K_L \to \pi^0 e^+ e^-$ also has sensitivity to the CKM parameter η through its CP-violating component. There are both direct and indirect CP-violating amplitudes which can interfere. The direct CP-violating amplitude is short distance dominated and has been calculated in detail within the SM [9]. The indirect CP-violating amplitude can be inferred from a measurement of $K_S \to \pi^0 e^+ e^-$. The complete CP-violating contribution to the rate can be written as [49]:

$$\mathrm{B}_{\mathrm{CPV}} \approx 10^{-12} \left[15.7 |a_S|^2 \pm 1.45 \left(\frac{|V_{cb}|^2 \bar{\eta}}{10^{-4}} \right) |a_S| + 0.129 \left(\frac{|V_{cb}|^2 \bar{\eta}}{10^{-4}} \right)^2 \right] \tag{5}$$

where the three terms correspond to the indirect CP violation, the interference, and the direct CP violation respectively. The parameter a_S has recently been extracted by NA48 from a measurement of the decay $K_S \to \pi^0 e^+ e^-$ with the result $|a_S| = 1.06^{+0.26}_{-0.21} \pm 0.07$ [50]. With current constraints on the CKM parameters this implies that

$$\mathrm{B}_{\mathrm{CPV}} \approx (17.2 \pm 9.4 + 4.7) \times 10^{-12}. \tag{6}$$

The indirect CP violation is larger than the direct CP violation. While the sign of the interference is *a priori* unknown, arguments in favor of a positive sign have been put forward in Ref. 51 and Ref. 52. NA48 has also obtained the value $a_s = 1.54^{+0.40}_{-0.32} \pm 0.06$ [53] from a measurement of the $K_S \to \pi^0 \mu^+ \mu^-$ rate, in agreement with the value extracted from $K_S \to \pi^0 e^+ e^-$

This mode also has a CP-conserving component dominated by a two-photon intermediate state that is still subject to a sizable uncertainty. This CP-conserving component can be decomposed into an absorptive and a dispersive part. The absorptive part can be extracted from the measurement of the low $m_{\gamma\gamma}$ region of the $K_L \to \pi^0 \gamma\gamma$ spectrum. The rate and the shape of the distribution $d\Gamma/dm_{\gamma\gamma}$ in $K_L \to \pi^0\gamma\gamma$ are well described in chiral perturbation theory in terms of three (a priori) unknown parameters [54,55]. Both KTeV and NA48 have studied the mode $K_L \to \pi^0\gamma\gamma$ reporting conflicting results. KTeV finds $B(K_L \to \pi^0\gamma\gamma) = (1.68 \pm 0.07_{\text{stat}} \pm 0.08_{\text{sys}}) \times 10^{-6}$ [56], whereas NA48 finds $B(K_L \to \pi^0\gamma\gamma) = (1.36 \pm 0.03_{\text{stat}} \pm 0.03_{\text{sys}} \pm 0.03_{\text{norm}}) \times 10^{-6}$ [57]. Furthermore, the NA48 data indicates a negligible rate in the low $m_{\gamma\gamma}$ region suggesting a very small CP-conserving component $B_{\text{CP}}(K_L \to \pi^0 e^+ e^-) \sim \mathcal{O}(10^{-13})$ [51,55,57]. KTeV, on the other hand, reports a larger rate in the low $m_{\gamma\gamma}$ region, which suggests a larger $B_{\text{CP}}(K_L \to \pi^0 e^+ e^-)$ between $1 - 2 \times 10^{-12}$ [56]. In addition to this difference between the two experiments, there remains some model dependence in the estimate of the dispersive part of the CP-conserving $K_L \to \pi^0 e^+ e^-$ [51].

The related process, $K_L \to \pi^0 \gamma e^+ e^-$, is potentially an additional background in some region of phase space [58]. This process has been observed with a branching ratio of $(2.34 \pm 0.35_{\text{stat}} \pm 0.13_{\text{sys}}) \times 10^{-8}$ [59].

The decay $K_L \to \gamma\gamma e^+ e^-$ constitutes the dominant background to $K_L \to \pi^0 e^+ e^-$. It was first observed by BNL-845 [60] and subsequently confirmed with a much larger sample by FNAL-799 [61]. It has been estimated that this background will enter at about the 10^{-10} level [62,63], comparable to or larger than the signal level. Because of this, the observation of $K_L \to \pi^0 e^+ e^-$ at the SM level will depend on background subtraction with good statistics. Possible alternative strategies are discussed in Ref. 51 and references cited therein.

The 90% CL upper bound for the process $K_L \to \pi^0 e^+ e^-$ is 2.8×10^{-10} [63]. For the closely related muonic process, the published upper bound is $\mathrm{B}(K_L \to \pi^0 \mu^+ \mu^-) \leq 3.8 \times 10^{-10}$ [64] compared with the SM prediction of $(1.5 \pm 0.3) \times 10^{-11}$ [65] (assuming positive interference between the direct- and indirect-CP violating components). KTeV has additional data corresponding to about a factor 1.3 in sensitivity for the latter reaction that is under analysis.

A recent study of $K_L \to \pi^0 \mu^+ \mu^-$ has indicated that it might be possible to extract the direct CP-violating contribution by a joint study of the Dalitz plot variables and the components of the μ^+ polarization [66]. The latter tends to be quite substantial so that large statistics may not be necessary.

E. Other long distance dominated modes:

The decays $K^+ \to \pi^+ \ell^+ \ell^-$ ($\ell = e$ or μ) have received considerable attention. The rate and spectrum have been measured for both the electron and muon modes [67,68]. Ref. 49 has proposed a parameterization inspired by chiral perturbation theory, which provides a successful description of data but indicates the presence of large corrections beyond leading order. More work is needed to fully understand the origin of these large corrections.

Much information has been recorded by KTeV and NA48 on the rates and spectrum for the Dalitz pair conversion modes $K_L \to \ell^+ \ell^- \gamma$ [69,70], and $K_L \to \ell^+ \ell^- \ell'^+ \ell'^-$ for $\ell, \ell' = e$ or μ [16,70–72]. All these results are used to test hadronic models and could further our understanding of the long distance component in $K_L \to \mu^+ \mu^-$.

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