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REVIEW OF RARE KAON DECAY EXPERIMENTS

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ABSTRACT

Recent results on rare kaon decays are reviewed and prospects for future experiments are discussed.

1 Introduction

In recent years the study of the rare decays of kaons has had three major motivations. The first is the search for physics beyond the Standard Model (SM). Virtually all attempts to redress the theoretical shortcomings of the SM predict some degree of lepton flavor violation (LFV). Decays such as $K_L \rightarrow \mu^{\pm}e^{\mp}$ have very good experimental signatures and can consequently be pursued to remarkable sensitivities. These sensitivities correspond to extremely high energy scales in models where the only suppression is that of the mass of the exchanged field. There are also theories that predict new particles created in kaon decay or the violation of symmetries other than lepton flavor.

Second are decays that are allowed by the SM, but which are extremely suppressed. In the most interesting of these the leading contribution is a G.I.M.-suppressed [1] one-loop process that is quite sensitive to fundamental SM parameters such as V_{td} and m_t. These decays are also potentially very sensitive to BSM (Beyond the Standard Model) physics.

Finally there are a number of long-distance-dominated decays which serve as an arena for testing theoretical techniques such as chiral Lagrangians that seek to explain the low-energy behavior of QCD. Knowledge of certain of these decays is also needed to extract more fundamental information from some of the one-loop processes.

This field has been quite active in the last few years as can be established by Table 1 that lists the decays for which results have been announced in the last couple of years as well as those that I happen to know are under analysis. Thus one must be quite selective in a short review such as this.

Table 1: *Rare K decay modes under recent or on-going study.*

$K^+ \to \pi^+\nu\bar{\nu}$	$K_L \to \pi^0\nu\bar{\nu}$	$K_L \to \pi^0\mu^+\mu^-$	$K_L \to \pi^0 e^+e^-$
$K^+ \to \pi^+\mu^+\mu^-$	$K^+ \to \pi^+e^+e^-$	$K_L \to \mu^+\mu^-$	$K_L \to e^+e^-$
$K^+ \to \pi^+e^+e^-\gamma$	$K^+ \to \pi^+\pi^0\nu\bar{\nu}$	$K_L \to e^\pm e^\mp\mu^\pm\mu^\mp$	$K^+ \to \pi^+\pi^0\gamma$
$K_L \to \pi^+\pi^-\gamma$	$K_L \to \pi^+\pi^-e^+e^-$	$K^+ \to \pi^+\pi^0e^+e^-$	$K^+ \to \pi^0\mu^+\nu\gamma$
$K_L \to \pi^0\gamma\gamma$	$K^+ \to \pi^+\gamma\gamma$	$K^+ \to \mu^+\nu\gamma$	$K^+ \to e^+\nu e^+e^-$
$K^+ \to \mu^+\nu e^+e^-$	$K^+ \to e^+\nu\mu^+\mu^-$	$K_L \to e^+e^-\gamma$	$K_L \to \mu^+\mu^-\gamma$
$K_L \to e^+e^-\gamma\gamma$	$K_L \to \mu^+\mu^-\gamma\gamma$	$K_L \to e^+e^-e^+e^-$	$K_L \to \pi^0e^+e^-\gamma$
$K^+ \to \pi^+\mu^+e^-$	$K_L \to \pi^0\mu^\pm e^\mp$	$K_L \to \mu^\pm e^\mp$	$K^+ \to \pi^-\mu^+e^+$
$K^+ \to \pi^-e^+e^+$	$K^+ \to \pi^-\mu^+\mu^+$	$K^+ \to \pi^+X^0$	$K_L \to e^\pm e^\pm\mu^\mp\mu^\mp$
$K^+ \to \pi^+\gamma$			

Those who want a more extensive discussion of this subject can find it in the review by Barker and Kettell [2].

2 Beyond the Standard Model

There were a number K decay experiments dedicated primarily to the subject of lepton flavor violation at the Brookhaven AGS during the 1980's and 90's. These advanced the sensitivity to such processes by many orders of magnitude.

There have also been several "by-product" results on LFV and other BSM topics from most of the other K experiments being pursued during this period. Table 2 summarizes the status of work on BSM probes in kaon decay.

Table 2: *Current 90% CL limits on K decay modes violating the SM. The violation codes are "LF" for lepton flavor, "LN" for lepton number, "G" for generation number,* [3]*, "H" for helicity, "N" requires new particle*

Process	Violates	Limit	Experiment	Reference
$K_L \to \mu e$	LF	4.7×10^{-12}	AGS-871	4)
$K^+ \to \pi^+ \mu^+ e^-$	LF	2.8×10^{-11}	AGS-865	5)
$K^+ \to \pi^+ \mu^- e^+$	LF, G	5.2×10^{-10}	AGS-865	6)
$K_L \to \pi^0 \mu e$	LF	4.4×10^{-10}	KTeV	7)
$K^+ \to \pi^- e^+ e^+$	LN, G	6.4×10^{-10}	AGS-865	6)
$K^+ \to \pi^- \mu^+ \mu^+$	LN, G	3.0×10^{-9}	AGS-865	6)
$K^+ \to \pi^- \mu^+ e^+$	LF, LN, G	5.0×10^{-10}	AGS-865	6)
$K_L \to \mu^\pm \mu^\pm e^\mp e^\mp$	LF, LN, G	1.36×10^{-10}	KTeV	8)
$K^+ \to \pi^+ f^0$	N	1.1×10^{-10}	AGS-787	9)
$K^+ \to \pi^+ \gamma$	H	3.6×10^{-7}	AGS-787	10)

It is clear that any deviation from the SM must be suppressed by many orders of magnitude. The LFV searches in particular have been the victims of their own success. The theories they were testing have been killed or at least forced to retreat to a point where meaningful tests in the kaon system would be very difficult. In addition to the high demands on kaon flux, these searches are beginning to become background limited. Analysis of existing data is continuing but no new kaon experiments are being planned. Currently interest in probing LFV has moved almost entirely to the muon sector.

3 One loop decays

The focus of experimental effort has shifted from LFV to "one-loop" decays. These are GIM-suppressed [1] decays dominated or at least significantly influenced by loops involving weak bosons and heavy quarks. These processes include $K_L \to \pi^0 \nu \bar{\nu}$, $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \mu^+ \mu^-$, $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$. In some of these, the one-loop contributions violate CP. In one,

$K_L \to \pi^0 \nu\bar{\nu}$, this contribution completely dominates the decay. The GIM-mechanism tends to enhance the contribution of heavy quarks in the loops, so that in the SM, these decays are sensitive to the product of couplings $V_{ts}^* V_{td}$, often written as λ_t. Although it is quite possible to analyze these decays in terms of the real and imaginary parts of λ_t [11], for comparison with results in the B system, it is more customary to discuss them in terms of the Wolfenstein parameters, A, ρ, and η. Fig. 1 shows the relationship of rare kaon decays to the unitarity triangle construction. The dashed triangle is the usual one whereas the solid triangle illustrates the information available from rare kaon decays. Note that the "unitarity point", (ρ, η) can be determined from either triangle, and any disagreement between the K and B determinations indicates physics beyond the SM. The branching ratio closest to each side of the triangle determines the length of that side. The arrows leading outward from those branching ratios point to processes that need to be studied either because they potentially constitute backgrounds, or because knowledge of them is required to relate the innermost branching ratios to fundamental parameters. $K_L \to \mu^+\mu^-$, which can determine the bottom of the triangle (ρ), is the process for which the experimental data is the best, but for which the theory is most problematical. $K_L \to \pi^0 \nu\bar{\nu}$, which determines the height of the triangle is theoretically the cleanest, but experiment is many orders of magnitude short of the SM-predicted level. $K^+ \to \pi^+ \nu\bar{\nu}$, which determines the hypotenuse is nearly as clean, and has been observed. Prospects for this latter process are probably the best of the three since it is already clear it can be exploited.

3.1 $K_L \to \mu^+\mu^-$

The short distance component to this decay is quite reliably calculable in the SM [12]. There is also a rather precise measurement of its branching ratio [13] based on some 6200 events: $B(K_L \to \mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}$. However this process is dominated by long distance effects, the largest of which is the absorptive contribution mediated by $K_L \to \gamma\gamma$, which accounts for $(7.07 \pm 0.18) \times 10^{-9}$. Subtracting the two, yields a 90% CL upper limit on the total dispersive contribution to $(K_L \to \mu^+\mu^-)$ of 0.37×10^{-9}. $K_L \to \gamma^*\gamma^*$ also gives rise to a dispersive contribution, which is much more difficult to calculate than the absorptive part, and which can interfere with the short-distance weak contribution that one is trying to extract. The difficulty is due to the

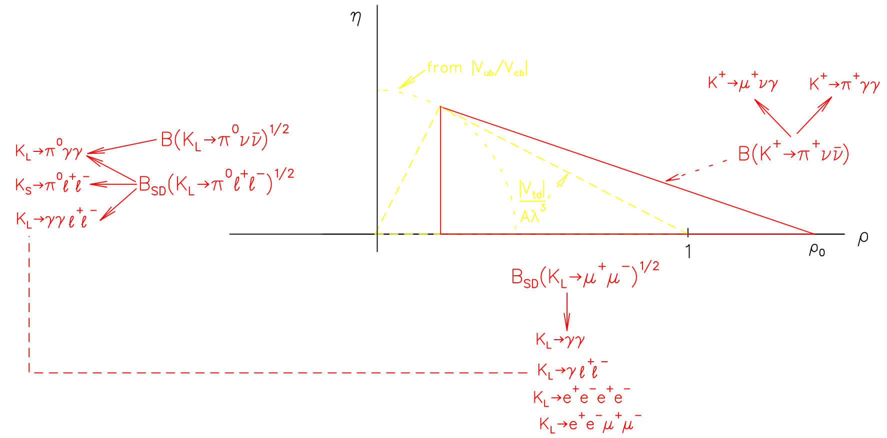

Figure 1: *K decays and the unitarity plane. The usual unitarity triangle is dashed. The triangle that can be constructed from rare K decays is solid. See text for further details.*

necessity of including intermediate states with virtual photons of all effective masses. Therefore such calculations can only partially be validated by studies of processes containing virtual photons in the final state. Recently there has been data on $K_L \to \gamma\mu^+\mu^-$ [14] (9327 events), $K_L \to e^+e^-e^+e^-$ [15] (441 events), and $K_L \to \mu^+\mu^-e^+e^-$ [8] (38 events) and there exist slightly older high statistics data on $K_L \to \gamma e^+e^-$ [16] (6864 events). Figure 2-left shows the $x = (m_{\mu\mu}/m_K)^2$ spectrum from Ref. [14]. The disagreement between the data (filled circles with error bars) and the prediction of pointlike behavior (histogram) clearly indicates the need for a form factor. A long-standing candidate for this is provided by the BMS model [17] and it depends on a single parameter, α_{K^*}.

Fig. 2-right shows three determinations of this parameter. It is clear that the level of agreement of the results leaves something to be desired. Fitting to a more recent parameterization of these decays [18] also results in a very marginal degree of agreement. This may improve when radiative corrections are properly accounted for. Thus additional effort, both experimental and theoretical, is required before the very good data on $K_L \to \mu^+\mu^-$ can be fully exploited.

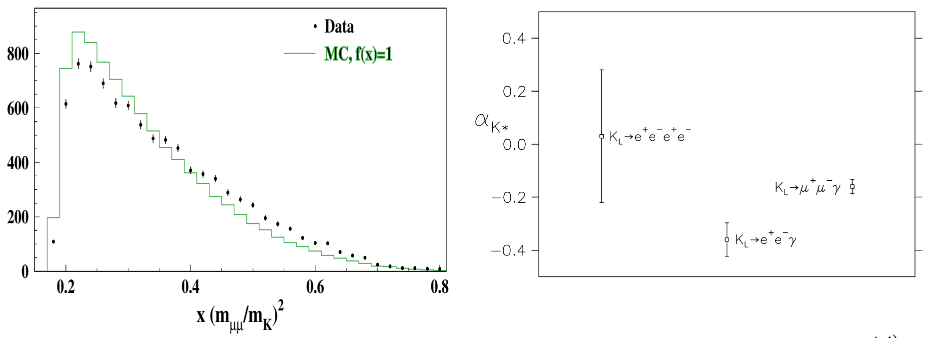

Figure 2: *Left: Spectrum of $x = (m_{\mu\mu}/m_K)^2$ in $K_L \to \mu^+\mu^-\gamma$ from Ref.* [14]. *Right: Determinations of the BMS parameter α_{K^*} from three K_L decays involving virtual photons.*

3.2 $K^+ \to \pi^+\nu\bar{\nu}$

Although its signature is much more challenging, $K^+ \to \pi^+\nu\bar{\nu}$ suffers from none of the long distance pollution afflicting $K_L \to \mu^+\mu^-$. In addition the hadronic matrix element, so often a problem, can be calculated to a couple of percent via an isospin transformation from that of K_{e3} decay [19]. Interest in $K^+ \to \pi^+\nu\bar{\nu}$ is driven in large part by its sensitivity to V_{td} (it is actually directly sensitive to the quantity $|V^*_{ts}V_{td}|$). Its amplitude is proportional to the dark slanted line at the right in Fig. 1. This is equal to the vector sum of the line proportional to $|V_{td}|/A\lambda^3$ and that from 1 to the point marked ρ_0. This length along the real axis is proportional to amplitude for the charm contribution to $K^+ \to \pi^+\nu\bar{\nu}$. The QCD corrections to this amplitude, which are the source of the largest theoretical uncertainty in the calculation of $B(K^+ \to \pi^+\nu\bar{\nu})$, have been calculated to NLLA [12]. The residual uncertainty in the charm amplitude is estimated to be $\sim 15\%$. This leads to a $\sim 6\%$ uncertainty [20] in extracting $|V_{td}|$ from $B(K^+ \to \pi^+\nu\bar{\nu})$. Experiment is still far from this level. So far AGS E787 has seen evidence for one event of $K^+ \to \pi^+\nu\bar{\nu}$ [9], leading to a branching ratio $B(K^+ \to \pi^+\nu\bar{\nu})= (1.5^{+3.4}_{-1.2}) \times 10^{-10}$. By comparison fits to the CKM phenomenology yield the expectation $(0.75 \pm 0.29) \times 10^{-10}$ [21]. E787 has a further sample of sensitivity $\sim 1.5 \times 10^{-10}$/event under analysis. A result is expected very soon. It is notable that E787 has established methods to reduce the residual background to $\sim 10\%$ of the the signal branching ratio predicted

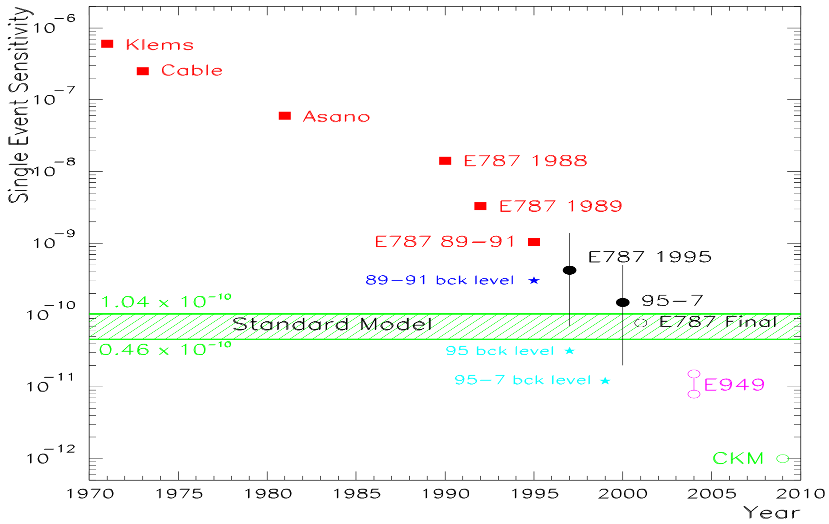

Figure 3: *History and projected future progress of the study of* $K^+ \to \pi^+ \nu\bar{\nu}$ *compared to the Standard Model expectation.*

by the SM.

A new experiment, AGS E949 [22], based on an upgrade of the E787 detector, is about to begin an engineering run. Data runs will occur in 2002-3. Using the entire flux of the AGS, it is expected to reach a sensitivity of $\sim 10^{-11}$/event. Fermilab has recently approved an experiment, CKM [23], to extend the study of $K^+ \to \pi^+ \nu\bar{\nu}$ by yet an another order of magnitude in sensitivity. This experiment, unlike all previous ones on this process, uses an in-flight, rather than a stopping K^+, technique. Fig. 3 shows the history and expectations of progress in studying this decay.

3.3 $K_L \to \pi^0 \nu\bar{\nu}$

$K_L \to \pi^0 \nu\bar{\nu}$ is the single most interesting measurement the K system can provide. It is direct CP-violating to a very good approximation [24, 25], like $K^+ \to \pi^+ \nu\bar{\nu}$ it has a hadronic matrix element that can be obtained from K_{e3}, but, unlike $K^+ \to \pi^+ \nu\bar{\nu}$, it has no significant charm contribution. As a result, the intrinsic theoretical uncertainty connecting $B(K_L \to \pi^0 \nu\bar{\nu})$ and the fundamental SM parameters is only about 2%.

$B(K_L \to \pi^0 \nu\bar{\nu})$ can be bounded indirectly by measurements of $B(K^+ \to \pi^+ \nu\bar{\nu})$ through a nearly model-independent relationship pointed out by Grossman and Nir [26]: $B(K_L \to \pi^0 \nu\bar{\nu}) < 4.4\, B(K^+ \to \pi^+ \nu\bar{\nu})$. The E787 result discussed above then yields $B(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-9}$ at 90% CL. This is far tighter than the current direct experimental limit, 5.9×10^{-7}, obtained by KTeV [28]. However to actually measure $B(K_L \to \pi^0 \nu\bar{\nu})$ at the SM level, one will need to improve on this by some five orders of magnitude. The KEK E391a experiment [27] does not quite propose to bridge this gap, but to achieve a sensitivity of $\sim 3 \times 10^{-10}$/event, which would at least better the indirect limit by an order of magnitude. It will serve as a test for a future much more sensitive experiment to be performed at the Japanese Hadron Facility. E391a features a carefully designed "pencil" beam, and a very high performance photon veto. The active photon detector is a CsI-pure crystal calorimeter. The entire rather compact apparatus will operate in vacuum. Beamline construction and tuning began in March 2000 and physics running is scheduled to start in the fall of 2003.

The KOPIO experiment [29] at BNL proposes to take a completely different approach, exploiting the intensity and flexibility of the AGS to make a high-flux, low-energy, microbunched K_L beam. The proposed experiment is shown in Fig. 4. The neutral beam will extracted at $\sim 45^o$ to soften the K_L spectrum sufficiently to allow time-of-flight determination of the K_L velocity. The large production angle also softens the neutron spectrum to the point where a large majority of the beam particles are below threshold for the hadroproduction of π^0's. The beam region will be evacuated to 10^{-7} Torr to further minimize such production. With a 10m beam channel for this low energy beam, the contribution of hyperons to the background will be negligible. K_L decays from a $\sim$ 3m fiducial region will be interrogated. The first detector element encountered by signal photons is a 2 X_0 preradiator capable of measuring their direction. An alternating drift chamber/scintillator plane structure allows energy measurement as well. A high-precision shashlyk calorimeter downstream of the preradiator will complete the energy measurement. With directional information, the decay vertex position can be determined. This then provides a measurement of the K_L 3-momentum so that kinematic constraints as well as photon vetoing are available against backgrounds. The leading expected background is $K_L \to \pi^0 \pi^0$, which is some eight orders of magnitude larger than the

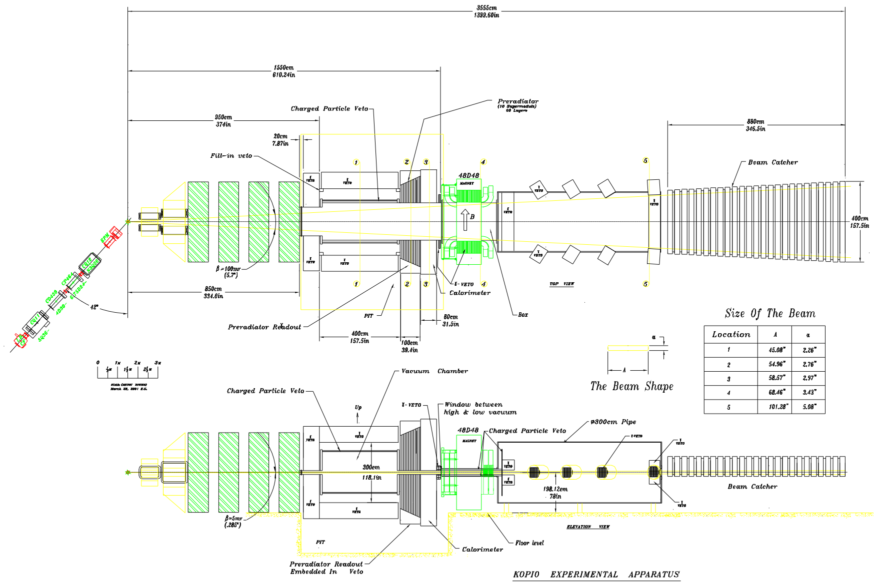

Figure 4: *Layout of the KOPIO detector.*

predicted signal. Since π^0's from this background have a unique energy in the K_L center of mass, a very effective kinematic cut can be applied. This reduces the burden on the photon veto system surrounding the decay region to the point where the hermetic veto techniques proven in E787 are sufficient. KOPIO aims to collect about 50 $K_L \to \pi^0 \nu \bar{\nu}$ events with a signal to background ratio of 2:1. This will permit η to be determined to $\sim$ 10%, given expected progress in measuring m_t and V_{cb}. KOPIO will run during the $\sim$20 hours/day the AGS is not needed for injection into RHIC.

4 Conclusions

Lepton flavor violation experiments have reached remarkable sensitivities, corresponding to mass scales of well over 100 TeV. But this success among other results has killed most models predicting LFV in kaon decay. Thus we are unlikely to see new dedicated experiments in this area for some time.

The precision measurement of $K_L \to \mu^+\mu^-$ will be very useful if theorists can make enough progress on calculating the dispersive long-distance amplitude.

$K^+ \to \pi^+ \nu\bar{\nu}$ can clearly be further exploited. There are two coordinated initiatives devoted to this: a 10^{-11}/event experiment currently just underway at the BNL AGS and a 10^{-12}/event experiment recently approved for the FNAL Main Injector. The first dedicated experiment to seek $K_L \to \pi^0 \nu\bar{\nu}$ is proceeding and an initiative at the AGS with the goal of making a $\sim$ 10% measurement of $Im(\lambda_t)$ is approved and in R&D.

The two $K \to \pi\nu\bar{\nu}$ results can determine an alternative unitarity triangle which will offer a critical comparison with results from the B system. If new physics is at work in the flavor sector, the two triangles will almost certainly disagree.

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