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Rare Kaon Decays

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The current status and future prospects in rare kaon decays are reviewed.

1. Introduction

The past few years have seen an evolution in the study of rare K decays from a concentration on explicitly Standard Model (SM) violating decays such as $K_L^0 \to \mu e$, to one on SM-allowed but suppressed decays such as $K \to \pi\nu\bar{\nu}$, in which short-distance interactions are dominant. There are also a number of recent experimental and theoretical studies of long-distance-dominated decays, but we do not have space to cover these, with the exception of those that are needed in the discussion of the short-distance-dominated processes.

2. Lepton Flavor Violation

The appeal of lepton flavor violating (LFV) decays is that (1) an observation immediately establishes the existence of new physics beyond the SM, (2) many theoretical approaches to extending or improving on the SM naturally predict LFV in K decays [1], (3) a number of these decays have very good experimental signatures and so can pursued to extremely high sensitivities, and (4) the scales accessed at these sensitivities in generic models are extremely high, of the order of 100 TeV.

There are new results in $K_L^0 \to e\mu$ and $K^+ \to \pi^+\mu^+e^-$. It is desirable to pursue both processes because the former is sensitive to pseudoscalar and axial vector currents while the latter is sensitive to scaler and vector currents. BNL-871 has set a 90% c.l. upper limit on $B(K_L^0 \to e\mu)$ of 4.7×10^{-12} [3]. This is the lowest limit yet reported on any particle decay. It represents the final result of E871 and no further improvement in sensitivity to this mode is likely for many years. BNL-865 has recently released a preliminary result from its 1996 run: $B(K^+ \to \pi^+\mu^+e^-) < 4.8 \times 10^{-11}$ which is about a factor 4 improvement on previous work [3]. Data taken in 1998 should further improve this sensitivity by a substantial factor. Table 1 summarizes the present situation in kaon LFV searches.

In a certain sense this type of experiment is a victim of its own success. Their sensitivities have advanced to the point where they contradict the particular theoretical models

Table 1
Status of lepton flavor violating K decays.

Mode	90% CL u.l.	Experiment	Year	Ref.	near future aim
$K^+ \to \pi^+ e\mu$	4.8×10^{-11}	BNL-865	1999	[2]	$\sim 6 \times 10^{-12}$ (BNL-865)
$K_L^0 \to \mu e$	4.7×10^{-12}	BNL-871	1998	[3]	
$K_L^0 \to \pi^0 e\mu$	3.1×10^{-9}	FNAL-799	1998	[4]	$\sim 5 \times 10^{-11}$ (KTeV)

that motivated them in the first place. The currently most popular theoretical approaches to going beyond the SM, such as the Minimal Supersymmetric Standard Model, in general do not predict LFV in kaon decay at accessible levels. Thus further progress in this area is likely to be mainly a by-product of other activities, such as the study of CP-violating and other suppressed decays. The study of $K_L^0 \to \pi^0 \mu e$ currently being carried out by the KTeV group is a good example.

3. Suppressed Decays

The interest in these decays is driven mainly by their potential to elucidate flavor physics, in particular the question of CP-violation.

3.1. $K \to \pi\nu\bar{\nu}$

The most interesting of these processes are the "golden" decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$. They are uniquely sensitive to $|V_{td}|$ and to the CKM CP-violation parameter η respectively. They are strongly GIM-suppressed and their leading contribution arises from loops involving weak bosons and heavy quarks. The connection between the rates of these processes and the fundamental parameters of the SM is extremely well-determined because the matrix element connecting the short-distance interaction to the initial and final state hadrons is measured by the rate of $Ke3$ decay [5]. The potential of these decays is illustrated in Fig. 1, where their relation to quantities measured in B decay is shown. Because these decays are suppressed down to the few $\times 10^{-11}$ level, they are also quite sensitive to physics beyond the SM. This has been emphasized lately by theorists attempting to explain the surprisingly large value of ϵ'/ϵ recently measured by the KTeV group [6]. Effects that are relatively small and difficult to discern in ϵ'/ϵ can be completely unmistakable in $K \to \pi\nu\bar{\nu}$ [7,8].

With two unobservable particles in the final state, these decays present very difficult experimental challenges, but their potential is so great that they are being quite actively pursued.

3.1.1. $K^+ \to \pi^+\nu\bar{\nu}$

For many years AGS E787 has been on the trail of $K^+ \to \pi^+\nu\bar{\nu}$. A solenoidal spectrometer, shown in Fig. 2 is situated at the end of a very intense low energy separated beam.

As many as 3×10^6 K^+/AGS pulse are stopped in a scintillating fiber target in the

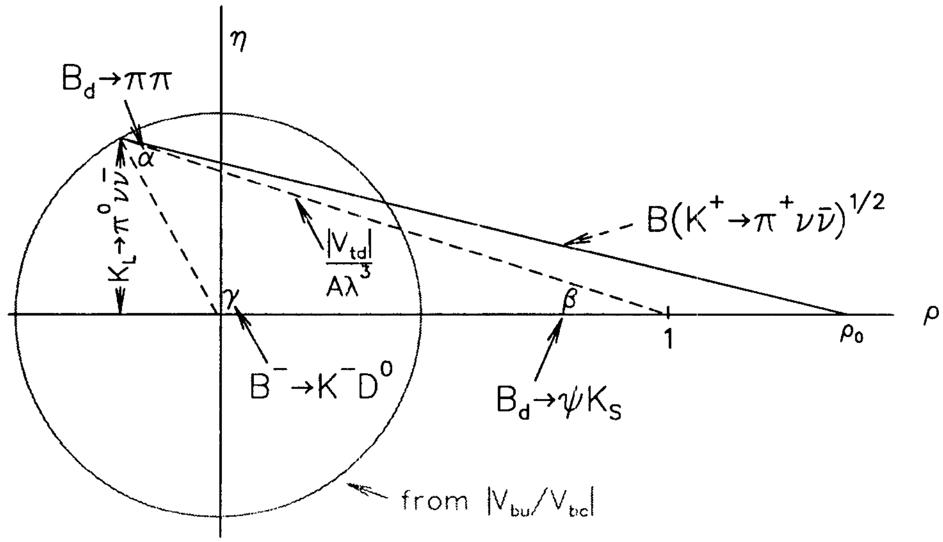

Figure 1. $K \to \pi\nu\bar{\nu}$ and the unitarity triangle.

center of the detector and charged decay products are tracked through the target, a cylindrical drift chamber and into a cylindrical array of scintillators and drift chambers ("Range Stack") where they range out. Pions are identified by kinematic correlation ($\frac{dE}{dx}$/total energy/range/momentum) and by observing their $\pi^+ \to \mu^+ \to e^+$ decay chain in the stopping scintillators. Photon detectors surround the Range Stack, and the entire apparatus serves as an hermetic veto for extra tracks. These techniques have been perfected over many years and the backgrounds have been reduced to 10^{-11}/event, which is sufficient for a measurement at the SM level. The data through 1997 have been analyzed and the result is shown in Fig 3 as a plot of pion range vs kinetic energy for candidates passing all other cuts.

The single point falling into the signal region is the famous 1995 event [9]. The normalization of this data set is not yet complete, but the sensitivity is $2-3$ times that of the earlier publication. This means that the central value of the previous result, $B(K^+ \to \pi^+\nu\bar{\nu}) = (4.2^{+9.7}_{-3.5}) \times 10^{-10}$, will fall almost into the range predicted by fits to the CKM matrix (the BR would need to fall outside the range $(0.5-2.0) \times 10^{-10}$ to pose a problem for the SM [10]). E787 has collected approximately twice the sensitivity of the sample shown in Fig. 3. It will have improved the sensitivity to $K^+ \to \pi^+\nu\bar{\nu}$ by a thousand-fold from the inception of the experiment, but this will still not exhaust the potential of this decay. To establish conclusively whether there is a conflict with the SM in this process or to get a useful measurement of $|V_{td}|$, a more sensitive experiment will be needed. Thus a successor experiment, AGS E949, has been proposed [11].

E949 exploits the fact that now that the AGS is primarily an injector to RHIC, it will only serve at most one or two proton experiments at any one time. Thus much larger proton currents can be devoted to a $K^+ \to \pi^+\nu\bar{\nu}$ experiment, and the accelerator running mode can be highly optimized for this work. This allows a large increment in sensitivity to be made with only modest hardware upgrades. In this way, a sensitivity of $\sim 10^{-11}$/event can be achieved in two or three years of running. In the longer term, to go beyond this

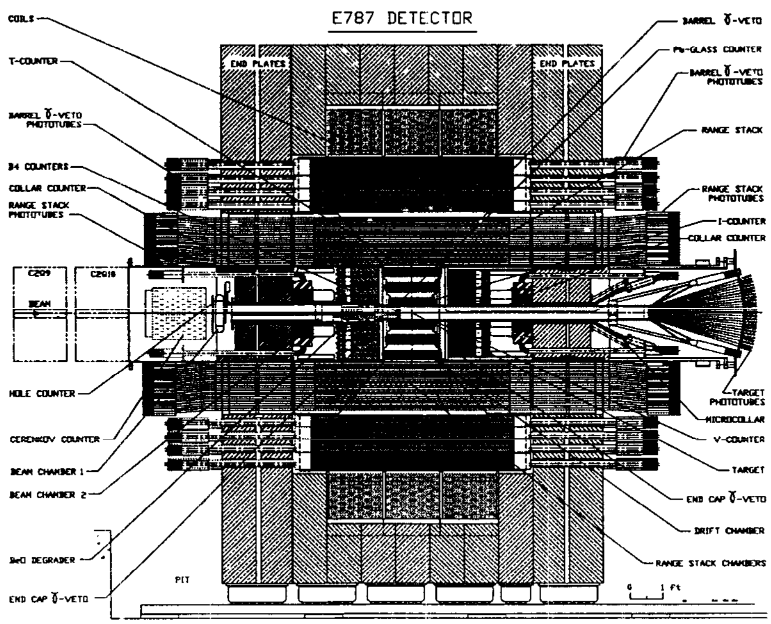

Figure 2. AGS E787 detector.

level, the CKM experiment [12] has been proposed for the Fermilab Main Injector. This is an in-flight experiment designed to reach the 10^{-12}/event level. At this point the experimental precision will be comparable to that currently claimed by theory in the SM.

3.1.2. $K_L^0 \to \pi^0 \nu \bar{\nu}$

In the Standard Model the rare decay $K_L^0 \to \pi^0 \nu \bar{\nu}$ is an uniquely sensitive probe of direct CP violation [13,14]. There are as yet no results from dedicated experiments to measure this decay. The best limit was recently obtained by the KTeV collaboration at FNAL [15] using the Dalitz decay mode of the π^0 ($\pi^0 \to e^+ e^- \gamma$). The KTeV detector is shown in Fig. 4. The basic principle of this experiment is the reconstruction of the decay vertex position of the π^0s and selection of events with high π^0 momentum transverse to the K_L^0 beam direction (p_T) to suppress backgrounds. No signal events were observed and a 90% c.l. upper limit $B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$ was obtained. Ultimately, this experiment is expected to reach the $\sim 10^{-8}$/event level of sensitivity, with a residual background of ~ 3 events.

The on-going KLOE experiment at DAΦNE, designed to measure ϵ'/ϵ, can achieve a sensitivity of 10^{-9} to $B(K_L^0 \to \pi^0 \nu \bar{\nu})$ [16]. However, dedicated experiments will be needed for the measurement of $K_L^0 \to \pi^0 \nu \bar{\nu}$ at the Standard Model level and beyond. Three such experiments have been proposed at FNAL, KEK and BNL. To observe and measure $K_L^0 \to \pi^0 \nu \bar{\nu}$ with reasonable accuracy, they plan to detect the π^0 through its $\pi^0 \to 2\gamma$ decay.

The KAMI approach [17] exploits a high energy pencil K_L^0 beam. The longitudinal coordinate of the vertex is determined through the reconstruction of the π^0 invariant mass

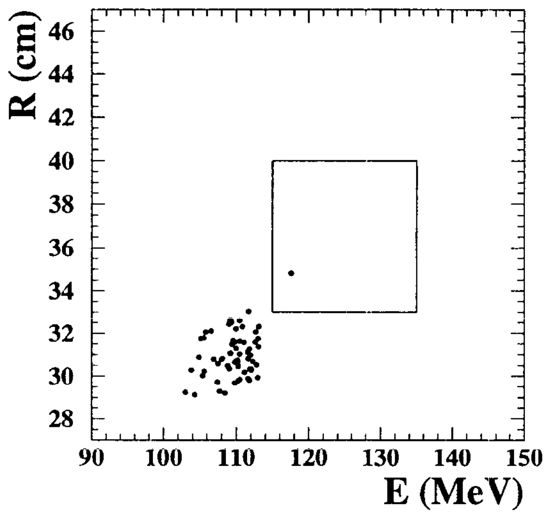

Figure 3. Range versus kinetic energy of π^+ for $K^+ \to \pi^+\nu\bar{\nu}$ candidates from AGS E787. The inner rectangle bounds the signal region. The cluster of events to the lower left is residual $K^+ \to \pi^+\pi^0$ background.

and then p_T is extracted. An extremely good photon veto system with $\sim 10^{-6}$/photon inefficency for high energies and better than 10^{-2}/photon for low energies is needed in this experiment. The first stage of this experiment is designed to collect about 30 $K_L^0 \to \pi^0\nu\bar{\nu}$ events per year with a signal/background ratio of $\sim$ 2. In the second stage the production target will be moved closer to the apparatus, allowing an increase in the signal/background ratio and the accumulation of about 120 events/year.

An experiment that utilizes a similar approach with an optimization for lower kaon energies is under preparation at KEK [18]. The main features of this experiment are a very narrow pencil beam, an efficient photon veto system and a CsI(pure) electromagnetic calorimeter. The acceptance to $K_L^0 \to \pi^0\nu\bar{\nu}$ is designed to be about 7%. Unfortunately, the available intensity of the 12 GeV KEK PS limits the sensitivity of this experiment to $\sim 10^{-10}$/event, *i.e.* about a factor 3 less than the $B(K_L^0 \to \pi^0\nu\bar{\nu})$ predicted by the Standard Model.

An alternative approach was taken in designing the E926 experiment at the AGS [19]. Fig. 5 illustrates the principles of E926. A $\sim$ 800 MeV/c K_L^0 beam can be obtained at 45° using a 24 GeV/c primary proton beam. Microbunching (σ ~200 psec) the AGS proton beam on extraction makes it possible to measure the momentum of K_L^0 by time-of-flight. The decay vertex and K_L^0 direction are determined by measuring both the directions and energies of the π^0 photons. This allows one to work in the K_L^0 center of mass system where π^0s from $K_L^0 \to \pi^0\pi^0$ have a unique energy and can be kinematically rejected without an excessive loss in acceptance. This full kinematic reconstruction of π^0's reduces the requirement on photon detection efficiency and makes it possible to suppress those kinematic configurations of $K_L^0 \to \pi^0\pi^0$ events with low energy missing photons. This approach allows the experiment to be done using a relatively compact detector with low background from π^0 produced by low energy beam neutrons and very suppressed

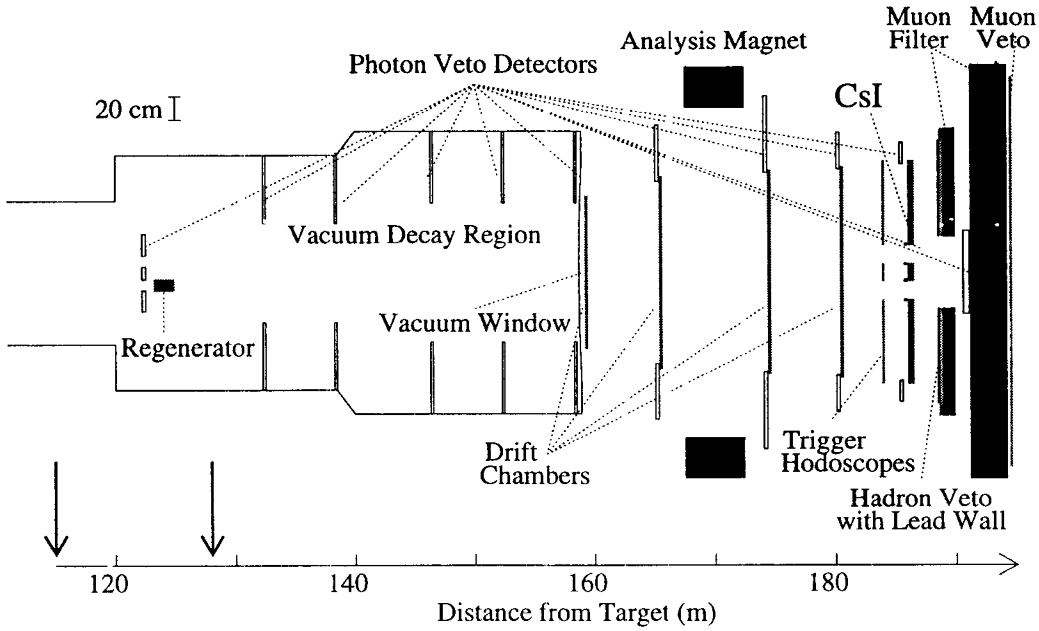

Figure 4. Schematic view of the KTeV experiment configured for rare decays.

background from hyperon decay.

A schematic view of the E926 detector is shown in Fig. 6. A 3.5 m long decay region, where about 16% of the K_L^0's decay, is surrounded by efficient veto counters, and a photon detector consisting of preshower and calorimeter in succession. A detector designed to veto photons travelling down the calorimeter beam hole is located behind the calorimeter. The beam region is evacuated to a level of 10^{-7} Torr to suppress neutron-induced π^0 production. In the forward detection region the photon detector consists of two parts: a 2 X_0 fine-grained preradiator in which the photons are converted and the first e^+/e^- pair is tracked, and an 18 X_0 calorimeter in which the remaining energy of the electromagnetic shower is measured. The preradiator must provide an accurate measurement of the photon positions ($\sigma =\sim 200\,\mu$m (rms)) and directions ($\sigma \sim$25 mr) in order to allow reconstruction of the K_L^0 decay vertex while also contributing to the requirement of sufficient energy resolution. Located 15 m downstream of the calorimeter, a beam hole photon detector ("beam catcher") is designed to veto decay photons whose trajectories are directly in the beam. A Pb/lucite detector, consisting of 50 layers of 1 mm lead and 5 mm lucite, is currently being considered, as is a Pb/aerogel device. The barrel veto detector will consist of lead-plastic scintillator sandwich counters with a thickness of 18 X_0 ($\sim$ 80 layers of 1 mm lead and 5-7 mm plastic scintillator).

The estimated acceptance of the detector for $K_L^0 \to \pi^0\nu\bar{\nu}$ is approximately 1% [19]. This includes the solid angle, photon conversion and reconstruction factors and phase space acceptance in addition to cuts on missing energy and mass and on photon energy sharing applied to suppress the major $K_L^0 \to \pi^0\pi^0$ backgrounds. Assuming the Standard Model central value for the $K_L^0 \to \pi^0\nu\bar{\nu}$ branching ratio, the expected number of detected $K_L^0 \to \pi^0\nu\bar{\nu}$ events to be accumulated in 9000 hours of beam at 10^{14} protons/spill is about

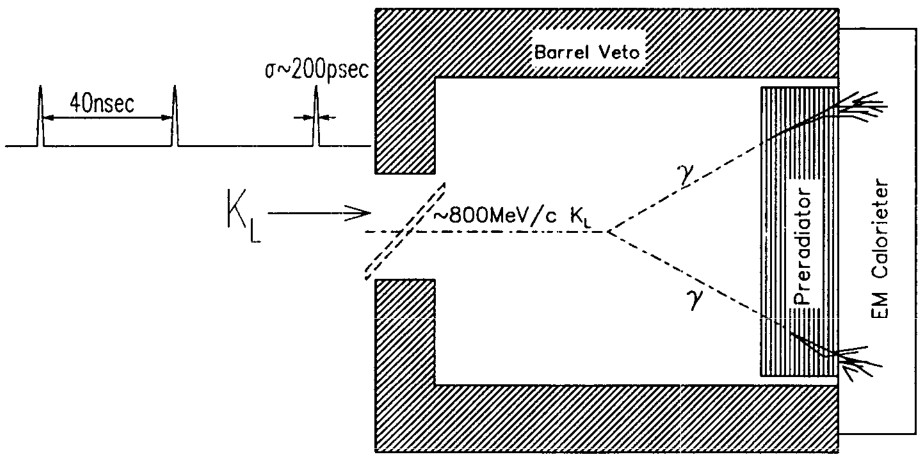

Figure 5. Principles of the E926 experiment.

50. The single event sensitivity of the experiment would be approximately 6×10^{-13}. The backgrounds which include other kaon decays, among which $K_L^0 \to \pi^0\pi^0$ dominates, neutron production of π^0s and $\Lambda \to n\pi^0$, are estimated to be suppressed to about 20% of the level of the expected signal.

3.2. Other suppressed decays

Since the golden decays are technically so difficult, it is fair to ask whether other, potentially more tractable processes could give equivalent information. The answer is a qualified "yes", because other K decays sensitive to short distance physics exist and indeed some of these are easier to detect than $K \to \pi\nu\bar{\nu}$. Unfortunately all of them suffer to a greater or less degree to "pollution" from long distance physics.

3.2.1. $K_L^0 \to \pi^0\ell^+\ell^-$

Two decays closely related to $K_L^0 \to \pi^0\nu\bar{\nu}$ are currently being actively pursued: $K_L^0 \to \pi^0e^+e^-$ and $K_L^0 \to \pi^0\mu^+\mu^-$. These probe very similar physics to the former decay, both in and beyond the SM. In principle one can measure η with these decays. However they also receive several other contributions that have to be disentangled before the short distance component can be extracted. We will couch the discussion of this in terms of $K_L^0 \to \pi^0e^+e^-$. The case of $K_L^0 \to \pi^0\mu^+\mu^-$ is very similar, and where it differs, the situation is generally less favorable. The SM direct CP-violating contribution to $B(K_L^0 \to \pi^0e^+e^-)$ $\approx (5 \pm 2) \times 10^{-12}$ [20]. This is approximately six times smaller than the corresponding contribution to $B(K_L^0 \to \pi^0\nu\bar{\nu})$, but at first sight the superior experimental signature should more than make up for this. However there are several other potentially comparable contributions to any observed signal, whose exact sizes are not easy to determine:

1. An indirect CP-violating component. The size of this contribution is proportional to the rate for $K_S^0 \to \pi^0e^+e^-$, which has never been observed. Efforts to relate this quantity to the well-measured $B(K^+ \to \pi^+e^+e^-)$ are rather model dependent and yield $B(K_L^0 \to \pi^0e^+e^-)|_{indir} \sim (1-5) \times 10^{-12}$, *i.e.* not necessarily smaller than

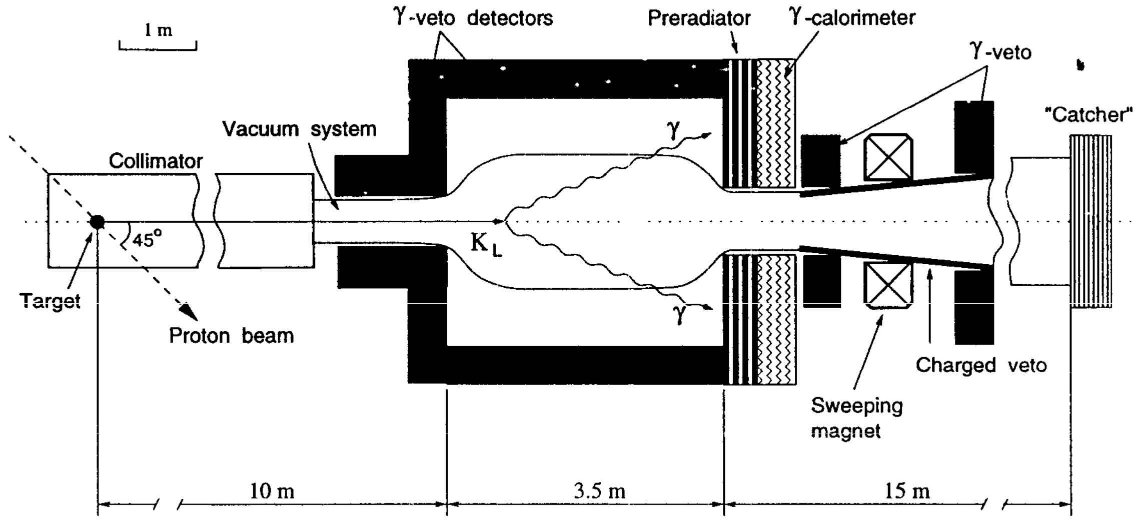

Figure 6. Schematic view of the E926 experiment.

the direct CP-violating component. To make matters even more interesting, (1) can interfere with part of the direct contribution [21].

2. A CP-conserving contribution from an intermediate $\pi^0\gamma\gamma$ state which in principle can be determined from studying the decay $K_L^0 \to \pi^0\gamma\gamma$. There is a recent measurement of $K_L^0 \to \pi^0\gamma\gamma$ by the KTeV group [22] where about 800 events were observed. This is a significant improvement over previous results both in statistics and kinematic coverage, but it is still not quite sufficient to predict $B(K_L^0 \to \pi^0 e^+e^-)|_{CP-cons}$ in a totally model-independent manner [23,24]. The results as found, $B(K_L^0 \to \pi^0\gamma\gamma) = (1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$ and effective vector coupling $a_V = -0.72 \pm 0.05 \pm 0.06$, lead to a prediction of $B(K_L^0 \to \pi^0 e^+e^-)|_{absorptive} \approx 1.3 \times 10^{-12}$. The dispersive part is somewhat more problematical. It is thought that the total contribution is in the neighborhood of 2×10^{-12}. Again this is not at all negligible compared to the expected direct CP-violating component.

3. An irreducible background from the process $K_L^0 \to e^+e^-\gamma\gamma$ when $m_{\gamma\gamma}$ happens to be near m_{π^0} [25]. Although the probability of this happening is small, since the total rate of $K_L^0 \to e^+e^-\gamma\gamma$ is four orders of magnitude larger than that of $K_L^0 \to \pi^0e^+e^-$, the former process is a serious limitation on the exploitation of the latter. There is a new result from KTeV on this process: $B(K_L^0 \to e^+e^-\gamma\gamma; E_\gamma^{cm} > 5\,MeV) = (6.31 \pm 0.14 \pm 0.42) \times 10^{-7}$ [26] (they have also observed $K_L^0 \to \mu^+\mu^-\gamma\gamma$ for the first time). As will be discussed below, this process has now probably been seen in the $K_L^0 \to \pi^0e^+e^-$ analysis as a residual background at about the 10^{-10} level. It will be a real challenge to extract detailed information about $K_L^0 \to \pi^0e^+e^-$ on top of a background of this magnitude.

4. A possible background from $K_L^0 \to \pi^0e^+e^-\gamma$ [27] when the γ is soft and escapes detection. The branching ratio for this decay is calculated to be in the range of a

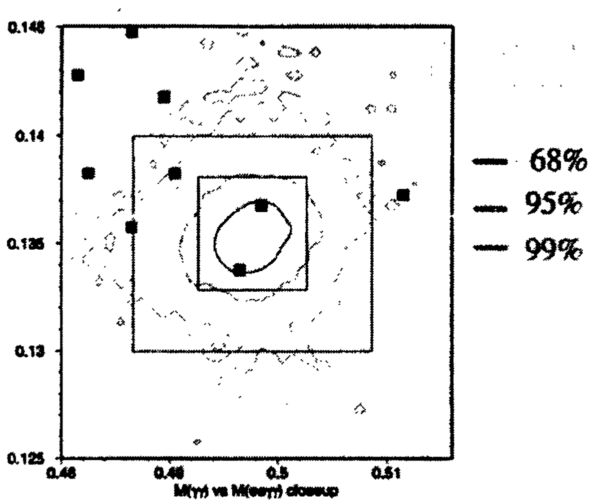

Figure 7. Events surviving the KTeV $K_L^0 \to \pi^0 e^+ e^-$ analysis.

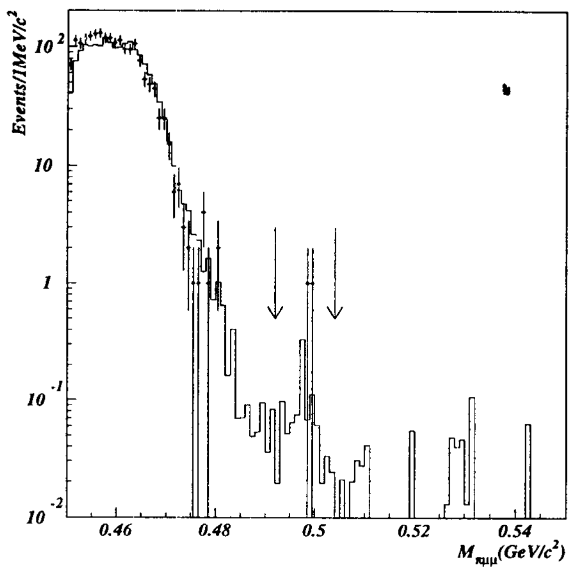

Figure 8. Result of KTeV $K_L^0 \to \pi^0 \mu^+ \mu^-$ analysis.

few $\times 10^{-8}$, so that it might be a serious background to $K_L^0 \to \pi^0 e^+ e^-$. However $K_L^0 \to \pi^0 e^+ e^- \gamma$ has recently been observed by KTeV and it is now not expected to constitute a major residual background [28].

Quite recently the KTeV experiment has announced results on both $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \mu^+ \mu^-$ [26] Fig. 7 is a plot of $m_{\gamma\gamma}$ vs $m_{ee\gamma\gamma}$ for events surviving the $K_L^0 \to \pi^0 e^+ e^-$ analysis. Two events fall within the accepted signal region compared with 1.5 expected background. The extracted 90% c.l. upper limit is 5.64×10^{-10}. This is an order of magnitude improvement on the previous limit, but there is still more than an order of magnitude to go to see $K_L^0 \to \pi^0 e^+ e^-$ at the SM level. With background already evident, this will not be easy. However in some supersymmetric scenarios [29] this BR can approach 10^{-10} so that it is certainly worthwhile to pursue it vigorously in the near term!

Fig. 8 is a histogram in $m_{\pi\mu\mu}$ of events surviving the KTeV $K_L^0 \to \pi^0 \mu^+ \mu^-$ analysis. As in case of $K_L^0 \to \pi^0 e^+ e^-$, there are two events in the signal region. The expected background is about one event. Note that the shape of the expected background peaks at the kaon mass, due to the presence of $K_L^0 \to \mu^+ \mu^- \gamma\gamma$. This analysis yields $B(K_L^0 \to \pi^0 \mu^+ \mu^-) < 3.4 \times 10^{-10}$ at 90% c.l. [26]. This again represents an order of magnitude improvement on previous results. Most of our remarks on the motivation and prospects for pursuing $K_L^0 \to \pi^0 e^+ e^-$ also pertain to this case. One difference is that the expected absolute size of the direct CP-violating component will be only about 20% of that for $K_L^0 \to \pi^0 e^+ e^-$. Another is that the relative size of the long distance component to the total is somewhat higher.

3.2.2. $K_L^0 \to \ell^+\ell^-$

The strangeness-changing neutral current process $K_L^0 \to \mu^+\mu^-$ has an important place in the history of weak interactions because of its role in inspiring the GIM mechanism [31]. In modern language, it has a short-distance contribution that depends sensitively on the CKM parameter ρ. QCD corrections to this contribution are well under control [32], so that $K_L^0 \to \mu^+\mu^-$ could in principle contribute a good deal to our knowledge of the unitarity triangle. Unfortunately, this component is overwhelmed by larger long-distance contributions, arising mainly from the $\gamma\gamma$ intermediate state. The largest part of this, the absorptive contribution arising from on-shell intermediate $\gamma\gamma$, is straightforwardly calculable [33] from the measured $K_L^0 \to \gamma\gamma$ rate. This so-called "unitarity bound" implies a minimum to the branching ratio of $(7.07\pm0.18)\times10^{-9}$. AGS Experiment 871 has recently reported a new, more precise experimental determination of $B(K_L^0 \to \mu^+\mu^-)$ [34]. Fig. 9 shows the $\mu^+\mu^-$ effective mass spectrum for events passing all other cuts. A clear peak containing some 6200 events is apparent. The branching ratio extracted from this sample is $(7.18\pm0.17)\times10^{-9}$. Note that there is a large contribution to the final 2.4% uncertainty from the 1.7% uncertainty on $B(K_L^0 \to \pi^+\pi^-)$, since E871 actually measures the ratio $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \pi^+\pi^-)$ to 1.6%. Although the new value for the branching ratio does not significantly exceed the unitary bound, it can be used to limit the value of possible new physics contributions [20]. The small difference between the measured branching ratio and the unitarity bound is the square of the dispersive amplitude, which itself is a sum of the short-distance and dispersive long-distance amplitudes. The latter is dominated by off-shell $\gamma\gamma$ intermediate states. This cannot be calculated in a model-independent way [35], but it is hoped that models for this purpose can be sufficiently refined by confrontation with data on $K_L^0 \to \ell^+\ell^-\gamma$ and $K_L^0 \to \ell^+\ell^-\ell'^+\ell'^-$ decay [36,37]. There are recent results on $K_L^0 \to e^+e^-\gamma$ from NA48 and on $K_L^0 \to e^+e^-e^+e^-$ and $K_L^0 \to e^+e^-\mu^+\mu^-$ from KTeV and a new result on $K_L^0 \to \mu^+\mu^-\gamma$ is expected soon from the latter experiment. The current results are summarized in Table 2 It remains to be seen if the new results agree in detail with models.

Table 2
Recent results on $K_L^0 \to \gamma\gamma^*$ and $K_L^0 \to \gamma^*\gamma^*$ decays

Mode	Branching ratio	events	Experiment	Year	Ref.
$K_L^0 \to e^+e^-\gamma$	$(1.06 \pm 0.02 \pm 0.02 \pm 0.04) \times 10^{-5}$	6854	NA48	1999	[38]
$K_L^0 \to e^+e^-e^+e^-$	$(4.14 \pm 0.27 \pm 0.31) \times 10^{-8}$	242	KTeV	1998	[39]
$K_L^0 \to e^+e^-\mu^+\mu^-$	(coming soon)	38	KTeV	1999	[40]

In the SM, the closely related decay $K_L^0 \to e^+e^-$ is completely dominated by long-distance effects, but these are more straightforward to calculate than in the case of $K_L^0 \to \mu^+\mu^-$. This renders $K_L^0 \to e^+e^-$ useless for constraining ρ, but the strong helicity suppression makes this process very sensitive to new pseudoscalar interactions. The window for such new physics has now been closed by the observation of this decay at the SM-predicted level by E871. Fig. 10 shows the E871 result on $K_L^0 \to e^+e^-$. Four events

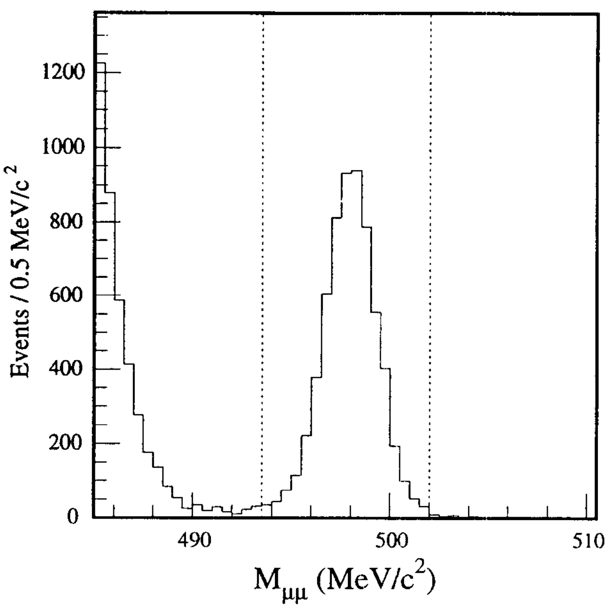

Figure 9. Two-body effective mass spectrum for $K_L^0 \to \mu^+\mu^-$ candidates from AGS-871.

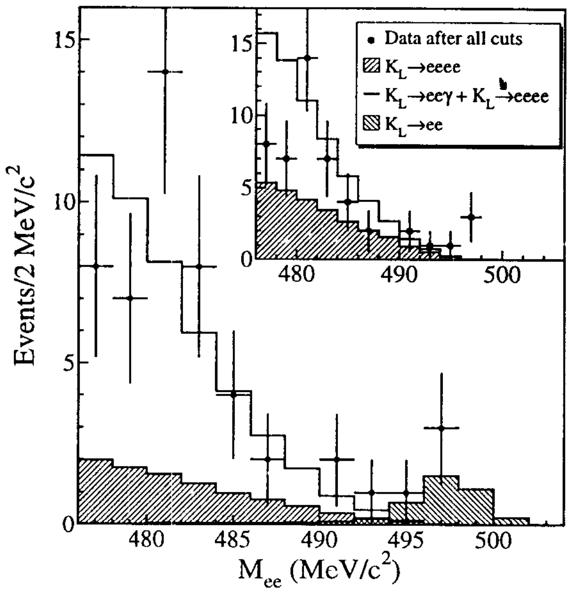

Figure 10. Two-body effective mass spectrum for $K_L^0 \to e^+e^-$ candidates from AGS-871.

were observed over a calculated background of 0.17 ± 0.10 of an event. This corresponds to $B(K_L^0 \to e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$, in close agreement with recent predictions [35,37]. It should be noted that this is the smallest branching ratio ever measured for a particle decay.

3.3. K's and B's

Fig. 11 shows the interrelations between the decays we have discussed and arranges them with respect to the CKM unitarity triangle. Note that apart from a scale factor that must be obtained from B decays (*i.e.* $|V_{cb}|$ or equivalent), rare kaon decays can in principle overdetermine the unitarity triangle. Note also that the version of the triangle shown as determined by rare K decays is a little different than that usually featured in advertising for the B system. This is helpful in keeping in mind that the unitarity information from the K system and that from the B system will in general **not** agree if new physics is in play [41], so that comparing the two constitutes an incisive test of the Standard Model.

4. T–Violation in K$^+$ Decays

The transverse muon polarization (P_T) in the decays $K^+ \to \pi^0\mu^+\nu$ ($K_{\mu3}$) and $K^+ \to \mu^+\nu\gamma$ ($K_{\mu2\gamma}$) provides a good opportunity for detecting CP–violation beyond the SM. This polarization vanishes in the SM, but it can be as large as $10^{-2} - 10^{-3}$ in models with multi-Higgs bosons, leptoquarks, left–right symmetry or SUSY [42,43]. Measurement of a non-zero transverse muon polarization in these decays would be a clear indication of physics beyond the SM and provide insight into the origin of CP violation. The present

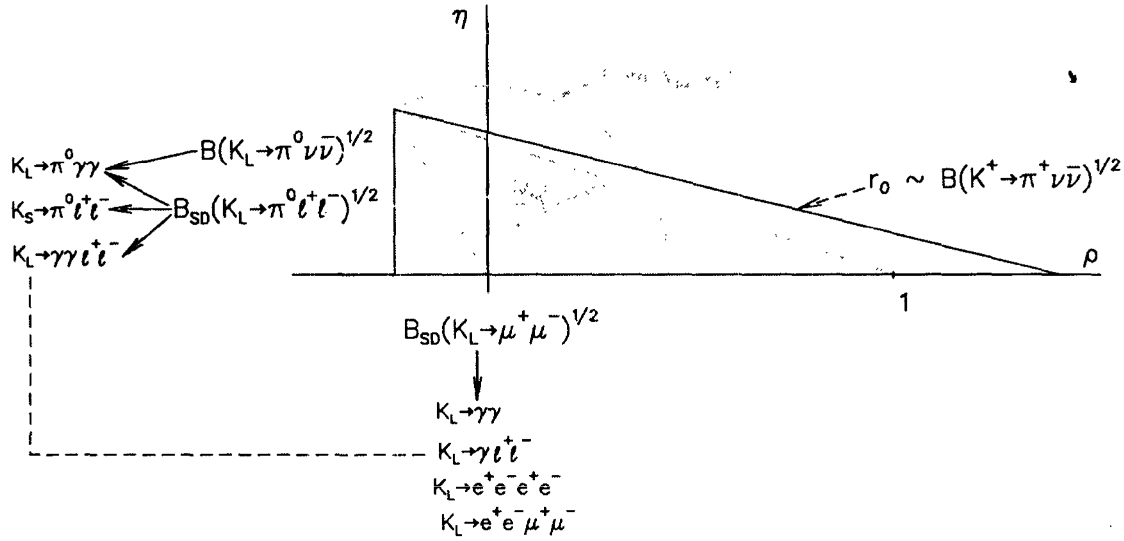

Figure 11. Rare kaon decays and the unitarity triangle. The notation 'B_{SD}' refers to the short-distance contribution to the decay.

experimental values of $P_T = (-3.1 \pm 5.3) \times 10^{-3}$ for $K_{\mu 3}$ and T-violating physics parameter $\mathrm{Im}(\xi) = (-1.6 \pm 2.5) \times 10^{-2}$, where $\xi(q^2)$ is defined as the ratio of two form factors, $f_+(q^2)$ and $f_-(q^2)$ in the $K_{\mu 3}$ decay matrix element [44], were obtained in Ref. [45]. No measurements of P_T in $K_{\mu 2\gamma}$ have been done yet.

In the on-going E246 experiment at KEK, which uses a stopped K^+ beam, P_T is measured as the azimuthal polarization of the muon emitted in the direction normal to the kaon beam for those $K_{\mu 3}$ events in which the π^0 is tagged to be either in the forward or backward direction relative to the beam. This method provides nearly total coverage of the decay kinematics for the isotropic decay of kaons at rest, separates events with forward- and backward-going pions, which have opposite signs of P_T, and cancels out most of spurious instrumental sources of false polarization, which are likely independent of the π^0 direction. The set-up is shown in Fig. 12. A 660 MeV/c kaon beam is stopped in an scintillating fiber target. $K_{\mu 3}$ events are identified by analyzing the μ^+s with the spectrometer and measuring π^0s by a CsI(Tl) photon detector. The muons exiting the spectrometer are stopped in a polarimeter (Fig. 12(c)) in which the decay positron asymmetry is measured in order to obtain P_T. The result presented at this Conference [46] is based on about 3.9×10^6 good $K_{\mu 3}$ events which have been analyzed from the data collected in 1996 and 1997. The result is consistent with no T–violation: $P_T = (-4.2 \pm 4.9(stat) \pm 0.9(sys)) \times 10^{-3}$ which gives $\mathrm{Im}(\xi) = (-1.3 \pm 1.6(stat) \pm 0.3(sys)) \times 10^{-2}$. Further improvement of the statistical error to about $\delta \mathrm{Im}(\xi) \sim 0.01$ is expected from the data accumulated in 1998 and after an additional run in 1999-2000 $\delta \mathrm{Im}(\xi) \sim (6-7) \times 10^{-3}$ can be obtained.

A new experiment, E923, planned at BNL [47] uses in–flight K^+ decays. A cylindrical active polarimeter around the kaon beam and an electromagnetic calorimeter will be used to reconstruct $K_{\mu 3}$ decays and suppress background. The detector acceptance to

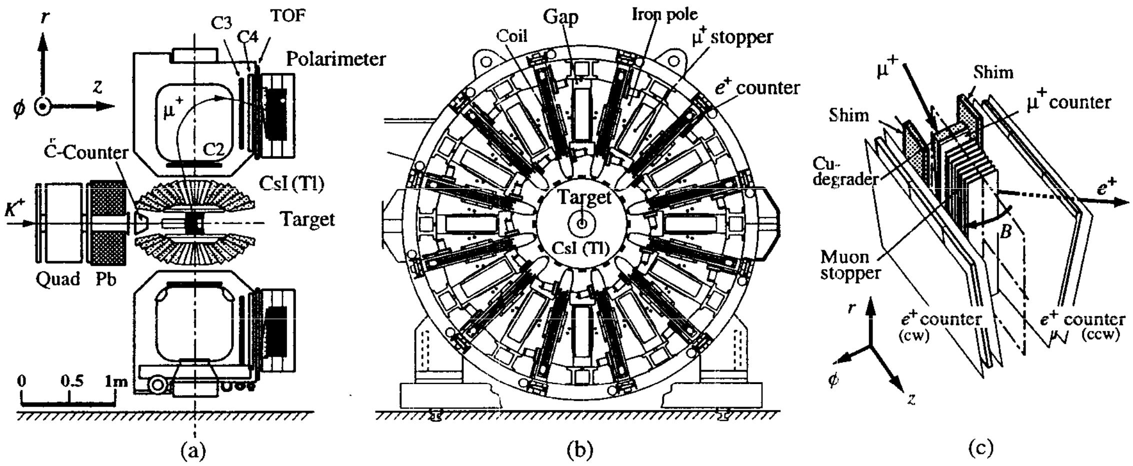

Figure 12. The layout of the KEK E246 detector:(a) side view, (b) end view and (c) one sector of the polarimeter.

$K_{\mu 3}$ events is about (2.5–2.7)$\times 10^{-5}$ per 2 GeV/c kaon. The advantage of the in–flight experiment is thus relatively high detector acceptance. The statistical sensitivity (1 σ level) to P_T in this experiment will be about 1.3×10^{-4} which corresponds to $\delta Im(\xi) = 7 \times 10^{-4}$. In this experiment sensitivity of $\leq 10^{-3}$ can be also obtained for P_T in $K_{\mu 2\gamma}$ decay.

5. Conclusions

Rare kaon physics is sufficiently active that in an article of limited length we have been forced to leave out many interesting topics, including recent results on the decays $K^+ \to \pi^+\ell^+\ell^-$, $K_L^0 \to \pi^+\pi^-e^+e^-$, $K_L^0 \to \pi^+\pi^-\gamma$, $K^+ \to \pi^+\pi^0\gamma$, $K^+ \to \ell^+\ell^-\ell'^+\nu$, $K^+ \to \pi^+X^0$, and others. But we hope to have conveyed the current vitality of the field of rare kaon decays where unprecedented sensitivities are being achieved and some of the most topical issues in particle physics are being addressed. Both Standard Model and non-SM CP-violation are being incisively probed and many promising windows for new physics are being explored.

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