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Rare Kaon Decay Experiments *

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Abstract

The current status of rare kaon decay experiments is reviewed. A large number of new results are available from several very sensitive experiments at BNL, FNAL and CERN. New limits in the search for Lepton Flavor Violation are discussed, as are new measurements of the CKM matrix.

1 Introduction

The study of rare kaon decays has played a key role in the development of the standard model (SM), and the field continues to have significant impact. Several recent reviews of the field are or will be soon available [1]. The two areas of greatest import are the determination of fundamental standard-model parameters, such as CKM [2] mixing and CP violation, and the search for physics beyond the standard model (BSM) through the search for lepton flavor violating (LFV) decays.

2 Lepton Flavor Violating Decays

There is solid experimental evidence for the exact conservation of an additive quantum number for each family of charged leptons. While there is no SM mechanism for LFV (non-zero m_ν induces LFV in the charged lepton sector at a level that is too small to observe), there is no underlying gauge symmetry preserving lepton flavor; and many extensions to the SM predict LFV. Observation of LFV would be unambiguous evidence for physics beyond the SM.

Due to the relatively long kaon lifetime, copious production at fixed target proton accelerators, and very sophisticated experimental techniques, the mass scale probed by rare kaon decay experiments is quite high. This can be seen by comparing the $K^\circ_L \to \mu e$ decay, through a hypothetical LFV vector boson with coupling g_X and mass M_X to the conventional $K_{\mu 2}$ decay (g and M_W): $M_X > 200$ TeV/c^2 $\times\, g_X/g \times [10^{-12}/\mathrm{B}(K^\circ_L \to \mu e\,)]^{1/4}$. For current experimental sensitivities at the level of 10^{-12}, mass scales in excess of 100 TeV are explored (for the usual electroweak coupling).

The E871 experiment at BNL, a search for $K^\circ_L \to \mu e$, has been completed, with two long runs during 1995–96. The E871 analysis of the data set used a 'blind analysis' technique, in which selection criteria were devised and backgrounds measured on the

*To be published in the *Proceedings of the Workshop on Strange Quarks in Hadrons, Nuclei, and Nuclear Matter; Athens, Ohio, May 12-13, 2000*; Ed. K. Hicks data outside of an exclusion region. These selection criteria were then applied to the remaining data and background measurements were compared to the actual number of events. No events were seen in the signal region (see Fig. 1), with an expected background of 0.1 events and the 90% CL limit on this decay is $B(K_L^\circ \to \mu e) < 4.7 \times$

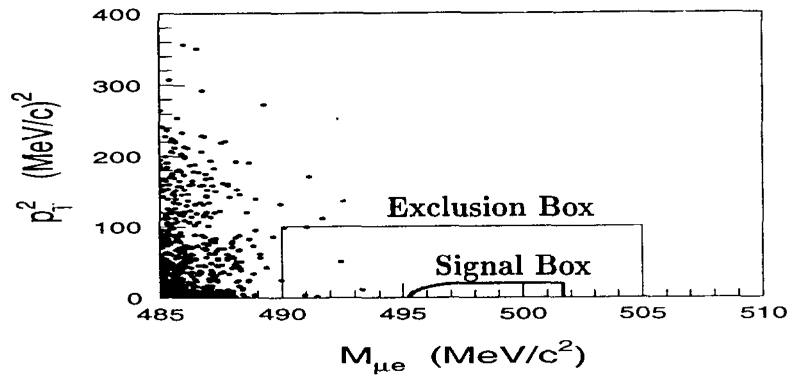

Figure 1: Final E871 data sample after all cuts, with no events in the signal region. The exclusion box was used to set cuts in an unbiased way on data far from the signal region. The shape of the signal box was optimized to maximize signal/background.

10^{-12} [3]. There are no plans to pursue this decay further.

The E865 experiment at BNL, designed to search for the decay $K^+ \to \pi^+ \mu^+ e^-$, an analog to $K_L^\circ \to \mu e$ which is sensitive to LFV interactions with different quantum numbers, collected data during 1995, 1996 and 1998. The 90% CL limits on this mode from the 1995 and 1996 runs are $B(K^+ \to \pi^+ \mu^+ e^-) < 2.1 \times 10^{-10}$ and $< 3.9 \times 10^{-11}$ respectively. Combining these results with that of the predecessor experiment E777, the 90% CL limit is $B(K^+ \to \pi^+ \mu^+ e^-) < 2.8 \times 10^{-11}$ [4]. The final sensitivity, including 1998 data, is expected to be ~3 times better. There are no plans to continue this search.

The current 90% CL limit for $K_L^\circ \to \pi^\circ \mu e$ is from E799-I [5] at FNAL, with $B(K_L^\circ \to \pi^\circ \mu e)$ $< 3.1 \times 10^{-9}$. This measurement has very little background, so E799-II (KTeV) will be able to substantially improve upon this limit, reaching sensitivities close to E865.

3 CKM Matrix

The $K \to \pi \nu \bar{\nu}$ modes: $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L^\circ \to \pi^\circ \nu \bar{\nu}$, are the 'golden modes' for determining CKM matrix parameters. Both of these modes can be very precisely calculated from fundamental SM parameters. The $K^+ \to \pi^+ \nu \bar{\nu}$ mode is sensitive to the magnitude of the poorly known $\lambda_t \equiv V_{ts}^* V_{td}$ and $K_L^\circ \to \pi^\circ \nu \bar{\nu}$ is purely direct-CP-violating and sensitive to $Im(\lambda_t)$.

Two other modes for which it may be possible to extract fundamental CKM parameters are $K_L^\circ \to \mu^+ \mu^-$ and $K_L^\circ \to \pi^\circ \ell^+ \ell^-$. However, in both cases, large long-distance contributions limit the usefulness of these modes. Additional measurements of some radiative kaon decays, as well as chiral perturbation theory (ChPT) work, are needed to extract the short distance physics [6-10]. In the case of $K_L^\circ \to \pi^\circ e^+ e^-$ and $K_L^\circ \to \pi^\circ \mu^+ \mu^-$, there are also significant backgrounds.

3.1 $K_L^\circ \to \mu^+\mu^-$ and $K_L^\circ \to \pi^\circ \ell^+\ell^-$

The mode $K_L^\circ \to \mu^+\mu^-$, whose small rate has played such an important role in the development of the SM (e.g. the GIM mechanism and the prediction of the charm quark [11]), has now been measured (relative to $K_L^\circ \to \pi^+\pi^-$) to the unprecedented precision of 1.5%, with 6200 events observed by E871 [12].

The decay $K_L^\circ \to \mu^+\mu^-$ is dominated by $K_L^\circ \to \gamma\gamma$ with the two real photons converting to a $\mu^+\mu^-$ pair. This contribution is precisely calculated using QED from a measurement of the $K_L^\circ \to \gamma\gamma$ branching ratio. There is also a long distance dispersive contribution through off-shell photons, which has been calculated [6,7] although there is some dispute as to the reliability of these calculations [8,9]. Most interesting is the short distance contribution, through internal quark loops, dominated by the top quark. A measurement of this short distance contribution is sensitive to the real part of the λ_t or, equivalently, the Wolfenstein [13] parameter ρ [14]:

$$B_{SD}(K_L^\circ \to \mu^+\mu^-) = 6.0 \times 10^{-3}[Re(\lambda_t) - 6.7 \times 10^{-5}]^2 \sim 9 \times 10^{-10} \qquad (1)$$

The current measurement of the branching ratio $\mathrm{B}(K_L^\circ \to \mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}$ by the E871 collaboration [12] represents a factor of three improvement. This value is only slightly above the unitarity bound from the on-shell two photon contribution of $\mathrm{B}_{abs}(K_L^\circ \to \mu^+\mu^-) = (7.07 \pm 0.18) \times 10^{-9}$ and leaves very little room for a short distance contribution. Using estimates of the long distance dispersive contribution [6], a 90% CL limit of $\rho > -0.33$ is obtained [12].

The decay $K_L^\circ \to e^+e^-$ is predominantly through two off-shell photons, making this decay less interesting for extracting SM parameters. However, the recent observation of four events by E871 [15], with $\mathrm{B}(K_L^\circ \to e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$ is consistent with ChPT predictions [7,8] and is the smallest branching ratio ever measured for any elementary particle decay.

The $K_L^\circ \to \pi^\circ \ell^+\ell^-$ modes can proceed via the direct-*CP*-violating processes. This short-distance contribution is given by [14]

$$B_{SD}(K_L^\circ \to \pi^\circ e^+e^-) = 2.5 \times 10^{-4}[Im(\lambda_t)]^2 \sim 5 \times 10^{-12}. \qquad (2)$$

The muon mode, $K_L^\circ \to \pi^\circ \mu^+\mu^-$, is expected to be five times smaller. Unfortunately, the decay $K_L^\circ \to \pi^\circ e^+e^-$ can occur in two other ways: an indirect-*CP*-violating contribution (which can be determined from measurement of $K_S^\circ \to \pi^\circ e^+e^-$) and a *CP*-conserving contribution (which may be calculated from the $K_L^\circ \to \pi^\circ \gamma\gamma$ rate at low invariant $\gamma\gamma$ mass). These contributions may be comparable to or larger than the direct-*CP*-violating contribution. Even more formidable is the background from $K_L^\circ \to \ell^+\ell^-\gamma\gamma$, as pointed out by Greenlee [16]. The KTeV experiment at FNAL, analyzing data from 1997, has significantly improved the limit on $K_L^\circ \to \pi^\circ e^+e^-$. Two events, consistent with the expected background of 1.1 events, were found in the signal region [17], giving a 90% CL limit of $\mathrm{B}(K_L^\circ \to \pi^\circ e^+e^-) < 5.6 \times 10^{-10}$. A similar analysis of the related muon mode resulted in two events, consistent with the expected background of 0.9 ± 0.2 events, in the signal region [18], and a slightly smaller upper limit, $B(K_L^\circ \to \pi^\circ \mu^+\mu^-) < 3.4 \times 10^{-10}$ (90% CL). Improvement in limits on both of these modes will be slow due to the presence of background.

There is a wealth of other new measurements in the kaon system reported recently from BNL, FNAL and CERN [1,19]. Many of these are useful for understanding long-distance effects in $K_L^\circ \to \mu^+\mu^-$ or $K_L^\circ \to \pi^\circ \ell^+\ell^-$ and for determining the background to $K_L^\circ \to \pi^\circ \ell^+\ell^-$. These measurements are substantially improved over previous values and even larger improvements will be obtained when the complete data sets are analyzed.

3.2 Golden Modes

The $K^+ \to \pi^+ \nu\overline{\nu}$ and $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ decays are the 'golden modes' for measuring CKM parameters; and, along with the other golden mode $B_d^\circ \to \psi K_S^\circ$ and perhaps the ratio of the mixing frequencies of B_s and B_d mesons, provide the best opportunity to over-constrain the unitary triangle and to search for new physics. The most powerful tests of our understanding of CP-violation and quark mixing will come from comparison of the results from B meson and kaon decays with little theoretical ambiguity. The two premier tests are expected to be:

- Comparison of the angle β from the ratio B($K_L^\circ \to \pi^\circ \nu\overline{\nu}$)/B($K^+ \to \pi^+ \nu\overline{\nu}$) and the CP asymmetry in the decay $B_d^\circ \to \psi K_S^\circ$ [20,21].
- Comparison of the magnitude $|V_{td}|$ from $K^+ \to \pi^+ \nu\overline{\nu}$ and the ratio of the mixing frequencies of B_s to B_d mesons [22].

The unitarity of the CKM matrix can be expressed as

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = \lambda_u + \lambda_c + \lambda_t = 0 \tag{3}$$

with the three vectors $\lambda_i \equiv V_{is}^* V_{id}$ converging to form a very elongated triangle in the complex plane. The first vector $\lambda_u = V_{us}^* V_{ud}$ is well determined from the decay $K^+ \to \pi^\circ e^+ \nu_e$ (K_{e3}). The height can be measured by $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ and the third side $\lambda_t = V_{ts}^* V_{td}$ will be measured by $K^+ \to \pi^+ \nu\overline{\nu}$. The decay $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ offers the best opportunity for measuring the Jarlskog invariant J_{CP} [23]. The $K \to \pi\nu\overline{\nu}$ decays are sensitive to the magnitude and imaginary part of λ_t. Measurements of these two modes, along with K_{e3}, will then completely determine the unitarity triangle.

The theoretical uncertainty in $K^+ \to \pi^+ \nu\overline{\nu}$ (~7%) is small and even smaller in $K_L^\circ \to \pi^\circ \nu\overline{\nu}$ (~2%); in both cases the hadronic matrix element is extracted from B(K_{e3}). The branching ratios have been calculated to next-to-leading-log approximation [24], complete with isospin violation corrections [25] and two-loop-electroweak effects [26]. Based on current understandings of SM parameters, the branching ratios can be expressed as [22]:

$$\begin{aligned} B(K^+ \to \pi^+ \nu\overline{\nu}\ ) &= \frac{\kappa_+ \alpha^2 B(K_{e3})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \sum_l |X_t \lambda_t + X_c^l \lambda_c|^2 & (4) \\ &= 3.6 \times 10^{-4}([Re(\lambda_t) - 1.4 \times 10^{-4}]^2 + [Im(\lambda_t)]^2) \\ &= (0.82 \pm 0.32) \times 10^{-10} \\ B(K_L^\circ \to \pi^\circ \nu\overline{\nu}\ ) &= \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\kappa_L \alpha^2 B(K_{e3})}{2\pi^2 sin^4\theta_W |V_{us}|^2} \sum_l |Im(\lambda_t) X_t|^2 & (5) \\ &= 1.6 \times 10^{-3}[Im(\lambda_t)]^2 = (3.1 \pm 1.3) \times 10^{-11}, \end{aligned}$$

where κ are the isospin corrections and the Inami-Lim functions [27], X_q, are functions of $x_q \equiv M_q^2/M_W^2$ where M_q is the mass of the quark q; these contain QCD corrections. In addition, it is possible to place a theoretically unambiguous upper limit on $K^+ \to \pi^+ \nu\overline{\nu}$ from the current limit on $B_s - \overline{B}_s$ mixing, B($K^+ \to \pi^+ \nu\overline{\nu}$) $<$ 1.67×10^{-10} [22].

3.2.1 $K^+ \to \pi^+ \nu\overline{\nu}$

The E787 experiment at BNL has recently published an analysis of the 1995–97 data sample [28]: one clean $K^+ \to \pi^+ \nu\overline{\nu}$ event lies in the signal box (see Fig. 2), with a

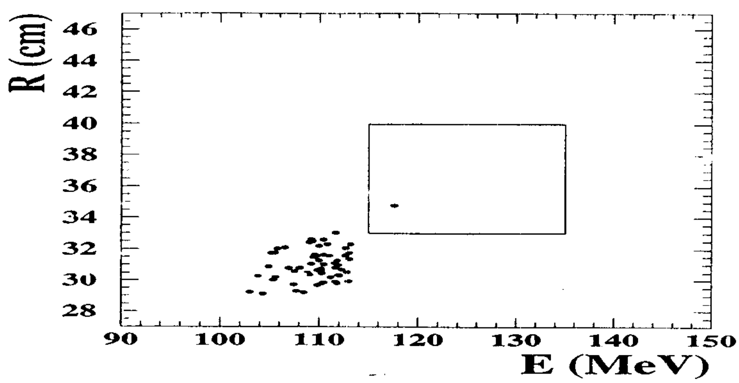

Figure 2: Final E787 data sample from the 1995–97 data set after all cuts. One clean $K^+ \to \pi^+ \nu\bar{\nu}$ event is seen in the box. The remaining events are $K^+ \to \pi^+ \pi^\circ$ background.

measured background of 0.08 ± 0.02 events. Based on this one event the branching ratio is $B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.5^{+3.4}_{-1.2} \times 10^{-10}$. From this measurement, a limit of $0.002 < |V_{td}| < 0.04$ is determined; in addition, the following limits on $\lambda_t \equiv V_{ts}^* V_{td}$ can be set: $|Im(\lambda_t)| < 1.22 \times 10^{-3}$, $-1.10 \times 10^{-3} < Re(\lambda_t) < 1.39 \times 10^{-3}$, and $1.07 \times 10^{-4} < |\lambda_t < 1.39 \times 10^{-3}$. The final sensitivity of the E787 experiment, based on data from 1995–98, should reach a factor of two further, to the SM expectation for $K^+ \to \pi^+ \nu\bar{\nu}$.

A new experiment, E949, is under construction and will run in 2001–03. Taking advantage of the very large AGS proton flux and the experience gained with the E787 detector, E949 with modest upgrades should observe $\mathcal{O}(10)$ SM events in a two year run. The background is well-understood and is $\sim$10% of the SM signal.

A proposal for a further factor of 10 improvement has been initiated at FNAL. The CKM experiment (E905) plans to collect 100 SM events, with $\sim$10 background events, in a two year run starting after 2005. This experiment will use a new technique, with K^+ decay-in-flight and momentum/velocity spectrometers.

3.2.2 $K_L^\circ \to \pi^\circ \nu\bar{\nu}$

The current best direct limit [29] on $K_L^\circ \to \pi^\circ \nu\bar{\nu}$ comes from the KTeV run in 1997: $B(K_L^\circ \to \pi^\circ \nu\bar{\nu}) < 5.9 \times 10^{-7}$ (90% CL).

An even more stringent limit can be derived in a model independent way [21] from the E787 measurement of $K^+ \to \pi^+ \nu\bar{\nu}$:

$$\begin{aligned} B(K_L^\circ \to \pi^\circ \nu\bar{\nu}) &< 4.4 \times B(K^+ \to \pi^+ \nu\bar{\nu}) \\ &< 2.6 \times 10^{-9} \text{ (90\% CL)} \end{aligned} \tag{6}$$

The next generation of $K_L^\circ \to \pi^\circ \nu\bar{\nu}$ experiments will start with E391a at KEK, which hopes to achieve a sensitivity of $\sim 10^{-10}$. Although the reach of E391a is not sufficient to observe a signal at the standard model level, the experiment will be able to rule out large BSM enhancements and learn more about how to do this difficult experiment. This experiment would eventually move to the JHF and aim for a sensitivity of $\mathcal{O}(10^{-14})$.

Two other experiments propose to reach sensitivities of $\mathcal{O}(10^{-13})$: E926 (KOPIO/RSVP) at BNL and E804 (KAMI) at FNAL. KAMI plans to reuse the excellent CsI calorimeter from KTeV and to operate at high kaon momentum to achieve good photon energy resolution and efficiency. It will take advantage of the large flux available from the Main Injector. KOPIO follows a different strategy; the kaon center of mass will be reconstructed using a bunched proton beam and a very low momentum K_L beam. This gives two independent criteria to identify background: photon veto and kinematics — allowing background levels to be directly measured from the data — and gives further confidence in any observed signal. The necessary flux will by obtained from the very high AGS proton current. The low energy beam also substantially reduces backgrounds from neutrons and hyperons. After three years of running, 65 SM events are expected with a S/B $\geq$ 2:1.

4 Conclusions and Future Prospects

The unprecedented sensitivities of rare kaon decay experiments in setting limits on LFV have constrained many extensions of the SM. The discovery of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ has opened the doors to measurements of the unitarity triangle completely within the kaon system. Significant progress in the determination of the fundamental CKM parameters will come from the generation of experiments that is now starting. Comparison with the B-system will then over-constrain the triangle and test the SM explanation of *CP* violation.

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