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Status of Rare *K* Decays

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Abstract

Recent experiments have achieved unprecedented sensitivites for rare decay modes of the K mesons. Results from experiments at BNL and KEK are described. These experiments search for lepton flavor violation in the decays $K_L^\circ \to \mu e$ and $K^+ \to \pi^+ \mu e$ and highly suppressed Standard Model decays, such as $K_L^\circ \to \mu^+\mu^-$ and $K^+ \to \pi^+ \nu\bar{\nu}$. New results on rare π° decays obtained in some of these experiments are also presented.

INTRODUCTION

My charge from the conveners was to report on "all of rare K decays excluding FNAL and CERN." The FNAL and CERN experiments were covered by Wah and Iconomidou-Fayard, respectively, in the same session. What is left is the very active program of experiments at BNL and KEK. At BNL, four experiments have produced results; three of these groups are working on major upgrades for the future. One group at KEK has recently completed an experiment and another group is setting up a new experiment. Given the severe time (and space) constraint, it is not possible to cover these experiments in much depth and a rather restricted selection of topics for emphasis is necessary. I regret having to gloss over much important work. I will address three general topics: (1) lepton flavor violation, (2) highly suppressed Standard Model decays, and (3) new results on rare π° decays obtained as a biproduct of these experiments. CP violation and in particular the mode $K_L^\circ \to \pi^\circ e^+ e^-$ will not be discussed; however, I note for completeness that the lowest limit on this mode as of the time of this conference is 5.5×10^{-9} from BNL E845.[1] (All limits in this paper are quoted for the 90% confidence level.)

LEPTON FLAVOR VIOLATION

The conservation of separate lepton number (e.g., muon number) is not understood at a fundamental level, in contrast for example to charge conservation, which is understood as a consequence of the gauge invariance of the electromagnetic interaction. Indeed, most of the widely discussed Standard Model extensions (e.g., extended technicolor, SUSY, right-left symmetry, multiple Higgs particles, etc.) provide mechanisms by which lepton flavor is not conserved and processes such as $K_L^\circ \to \mu e$ and $K^+ \to \pi^+ \mu e$ can occur. Searches for these and other lepton flavor violating decays provide a means of probing for such mechanisms at very high virtual mass scales. For exam-

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ple, for the $K_L^\circ \to \mu e$ decay, a branching ratio sensitivity of 10^{-11} probes a scale up to about 100 TeV.

The lowest currently published limit on $K_L^\circ \to \mu e$ is 9.4×10^{-10} from the KEK E137 experiment.[2] A lower sensitivity has been achieved in BNL E791. That experiment is shown in Figure 1. The experiment ran at the BNL AGS, where up to 5×10^{12} protons at 24 GeV were targeted on a one interaction length copper target, followed by sweeping magnets and collimators, to form a neutral beam. The detector was a two arm spectrometer, with two consecutive dipole magnets to assist with the rejection of backgrounds associated with pion decays in the spectrometer. Key features of the detector are precise tracking and kinematic reconstruction ($\sigma_{\rm mass} \simeq 1.4$ MeV), redundant particle identification for both electrons and muons, and a high rate data acquisition system.

Principal backgrounds are due to $K_L^\circ \to \pi e \nu$, where either the pion decays or both the pion and electron are wrongly identified. The E791 experiment has demonstrated background rejection down to at least the 10^{-11} level. Figure 2 shows a scatter plot of reconstructed mass for candidate μe pairs versus the square of the reconstructed transverse momentum p_T^2 (p_T is defined as the component of the vector sum of muon and electron momenta perpendicular to the direction of the parent K_L°). E791 ran at the AGS during 1988, 1989, and 1990. Figure 2 is the result of a combined analysis of 1989 and 1990 data sets, from which the preliminary limit on $K_L^\circ \to \mu e$ is 3.9×10^{-11}. When combined with the result[2] from running during 1988, the final E791 limit is 3.3×10^{-11}.

The KEK E137 experiment differed in details, but was very similar in philosophy. Neither experiment was background limited.

The $K_L^\circ \to \mu e$ decay would be sensitive to a new axial-vector or pseudoscalar interaction. The $K^+ \to \pi^+ \mu e$ decay is complimentary, since it would be sensitive to vector or scalar interactions. The recently completed BNL E777 has set an upper limit[3] of 2.1×10^{-10} on the mode $K^+ \to \pi^+ \mu^+ e^-$. The best limit on $K^+ \to \pi^+ \mu^- e^+$ is 6.9×10^{-9} from an older experiment.[4]

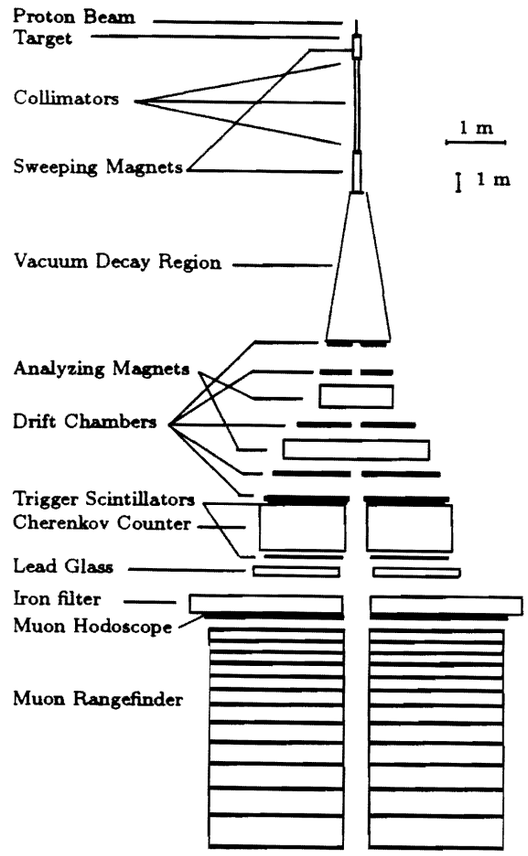

Figure 1. The BNL E791 neutral beam and detector.

HIGHLY SUPPRESSED DECAYS

Some highly suppressed Standard Model K decays provide a means of probing short-distance physics and are sensitive to Standard Model parameters such as the top quark mass and the CKM angles. Others are dominated by long-distance physics. Recent work toward understanding the latter cagegory depends on chiral perturbation theory. Quite

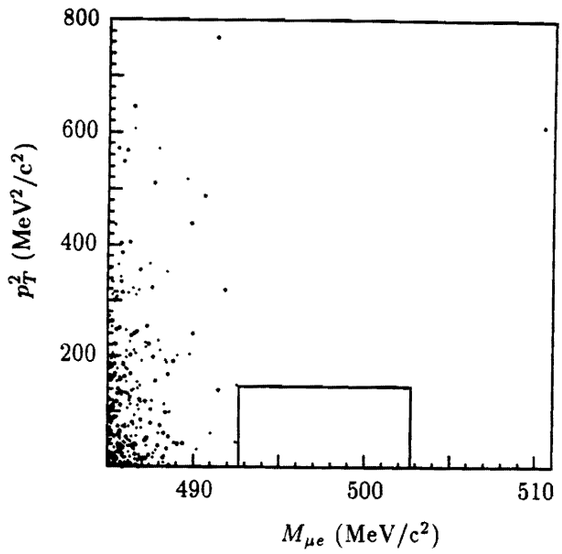

Figure 2. $K_L^\circ \to \mu e$ candidates from BNL E791. No events appear in the signal region.

often, it is necessary to understand the long-distance processes in order to isolate the short-distance effects of interest. Here, emphasis will be given to the decays $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^\circ \to \mu^+\mu^-$, both of which are sensitive to the top quark mass and the V_{td} element of the CKM matrix through the diagrams shown in Figure 3. Regretably, space does not permit discussion of decays in the second category, such as $K^+ \to \pi^+e^+e^-$, $K_L^\circ \to e^+e^-\gamma$, and $K_L^\circ \to e^+e^-e^+e^-$, for which recent results exist.

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

This process is dominated by the short-distance graphs of Figure 3. Long-distance effects should not be important, so a measurement of the branching ratio will provide a direct constraint on m_t and V_{td}. The branching ratio is expected to be close to 10^{-10} and so far the process has not been observed. If the decay is observed significantly above the Standard Model level, it would be an indication of new physics.

BNL E787 focuses on this mode. The experiment is performed in a "stopping" K^+ beam, so that the K^+'s decay at rest. The detector, shown in Figure 4, consists of an active scintillating fiber target, where the K^+'s are stopped. The target is surrounded by a cylindrical drift chamber, which in turn is surrounded by a plastic scintillator range stack (where pions stop and subsequently decay). Finally, a lead-scintillator photon veto system surrounds the range stack. A field of 1 Tesla is applied by a solenoidal magnet. The detector is virtually hermetic, with 4π coverage for vetoing photons.

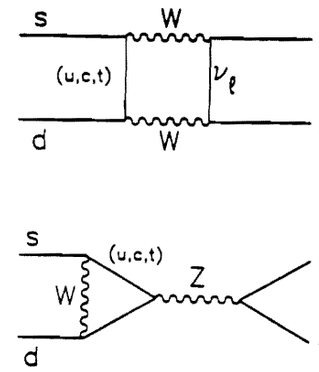

Figure 3. Diagrams for short-distance contributions to $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^\circ \to \mu^+\mu^-$.

The major backgrounds for $K^+ \to \pi^+\nu\overline{\nu}$ are the familiar decays $K^+ \to \pi^+\pi^\circ$ and $K^+ \to \mu^+\nu$. Both of these decays create a positively charged particle with a specific momentum, while the $K^+ \to \pi^+\nu\overline{\nu}$ creates a π^+ with a momentum distributed from 0 to 227 MeV, so that some rejection comes from simply avoiding the $K_{\pi 2}$ and $K_{\mu 2}$ peaks. Additional rejection of the $K^+ \to \pi^+\pi^\circ$ comes from vetoing the photons from the π°, which is done so efficiently that only about 2 in 10^6 π°'s are missed. Additional rejection against $K^+ \to \mu^+\nu$ is obtained by observing the full π^+ decay chain ($\pi \to \mu \to e$). This is accomplished by digitizing the photomultiplier signals from the range stack with 500 MHz 8-bit

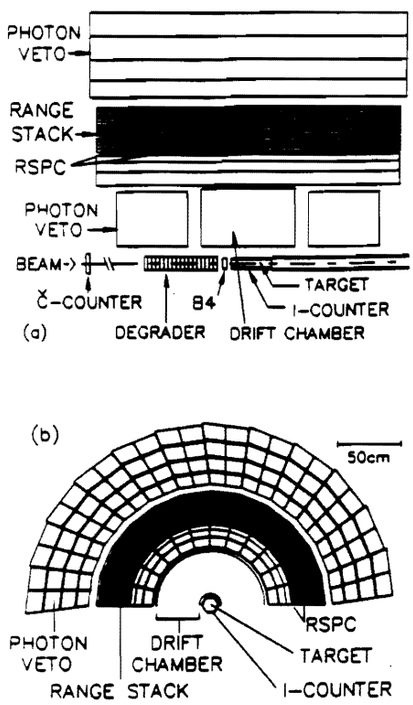

Figure 4. Upper half of the BNL E787 detector, showing (a) side and (b) end views.

transcient digitizers over a period of 10 μsec for each event.

The current upper limit from E787 on $K^+ \to \pi^+\nu\bar{\nu}$ is 5×10^{-9}. Data on tape should allow this to be improved by roughly a factor of two. This limit is from the region between the $K_{\pi 2}$ and $K_{\mu 2}$ peaks. The group has also demonstrated a capability to adequately reject backgrounds below the $K_{\pi 2}$. From a small sample of engineering data, they have established an independent limit from that region of 2×10^{-8}. In future running the sensitivity of the two regions should be comparable. After the decay is observed, measurements in both regions will make it possible to constrain the form of the decay matrix element.

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

This decay is dominated by the long-distance process $K_L^\circ \to \gamma\gamma \to \mu^+\mu^-$, which accounts for the so-called unitarity bound.[6] Using the measured $K_L^\circ \to \gamma\gamma$ rate, the two-photon contribution to the branching ratio of $K_L^\circ \to \mu^+\mu^-$ is $(6.8 \pm 0.3) \times 10^{-9}$. Extracting short-distance physics depends on understanding the long-distance contributions, both the unitarity contribution and also contributions from virtual intermediate two-photon states. This subject has been the focus of recent theoretical work[7], but has not progressed to the point where measurements of $K_L^\circ \to \mu^+\mu^-$ can be interpreted with confidence. Nonetheless, this mode has the advantage of having been observed with good statistics.

The KEK E137 experiment observed 179 events and the BNL E791 experiment over 700. This is to be compared with a prior world's sample of 33 events from five experiments. The KEK E137 branching ratio[8] is $(7.9 \pm 0.7) \times 10^{-9}$. The result from the BNL experiment is $(7.0 \pm 0.5) \times 10^{-9}$. This is still preliminary, although only the error bar is likely to change. Figure 5 shows the $\mu\mu$ mass peak for both of these experiments.

$K_L^\circ \to e^+e^-$

The Standard Model contributions to this decay are helicity suppressed. The unitarity bound is 3×10^{-12}. Above this level, the mode is sensitive to a new pseudoscalar strangeness changing neutral current interaction. The lowest published[2] limit at present is 16×10^{-11} from the KEK E137 experiment. A new limit from the BNL E791 experiment, for the full three year data set, is 4.1×10^{-11}.

RARE π° DECAYS

The decay $K^+ \to \pi^+\pi^\circ$ provides a means for rare K^+ decay experiments also to search for rare π° decays. Two new results are described below.

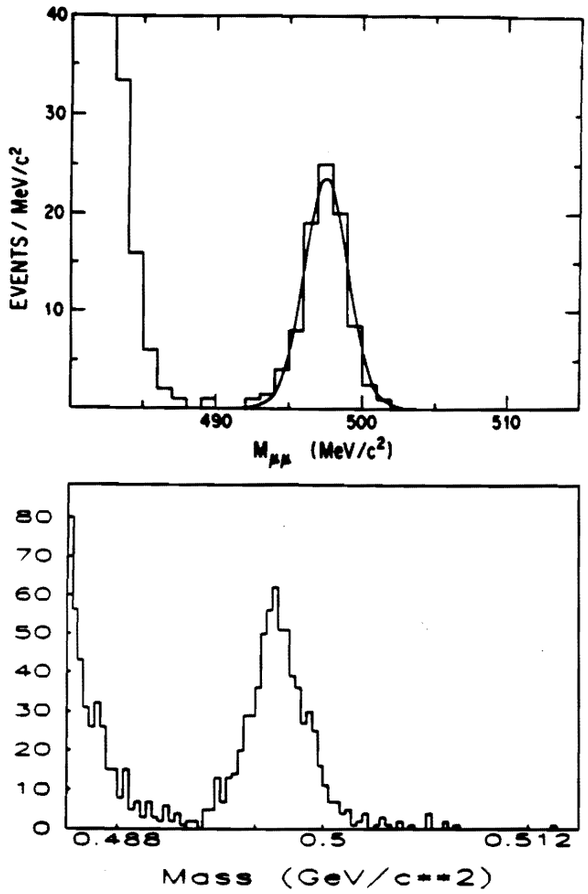

Figure 5. $K_L^\circ \to \mu^+\mu^-$ mass peak from KEK E137 (upper) and BNL E791 (lower).

$\pi^\circ \to e^+e^-$

The unitarity bound for this decay is 4.75×10^{-8}. A CERN PS experiment[9] reported $B(\pi^\circ \to e^+e^-) = 22^{+24}_{-11} \times 10^{-8}$ from tagged π°'s in a K^+ experiment. A LAMPF experiment[10] reported $B(\pi^\circ \to e^+e^-) = (17 \pm 6 \pm 3) \times 10^{-8}$, from π°'s produced via $\pi^- p \to n\pi^\circ$. Both experimental results were substantially above the unitarity prediction. Subsequent theoretical attempts[11] to account for this failed, leading to skepticism regarding these experiments. Also, the SINDRUM experiment[12] reported an upper limit of 13×10^{-8}.

BNL E851 (an extension of BNL E777, using the same apparatus) has produced a new result based on the observation of this decay. The backgrounds are single and double Dalitz decays ($\pi^\circ \to e^+e^-\gamma$ and $\pi^\circ \to e^+e^-e^+e^-$) were the photon or an e^+e^- pair is missed. These background sources are suppressed by requiring the reconstructed $\pi^+e^+e^-$ mass to be close to the K^+ mass. Figure 6 shows reconstructed e^+e^- mass for events with $\pi^+e^+e^-$ mass greater than 490 MeV. The data show a clear excess centered on the π° mass. The dashed curve in Figure 6 is Monte Carlo with no $\pi^\circ \to e^+e^-$ contribution and the dotted curve is Monte Carlo with the $\pi^\circ \to e^+e^-$ branching ratio at the value favored by the data. The BNL E851 result is $B(\pi^\circ \to e^+e^-) = (6.0 \pm 1.8) \times 10^{-8}$. This value is consistent with the unitarity prediction. (See also the talk of Wah, these proceedings, for FNAL results on this mode.)

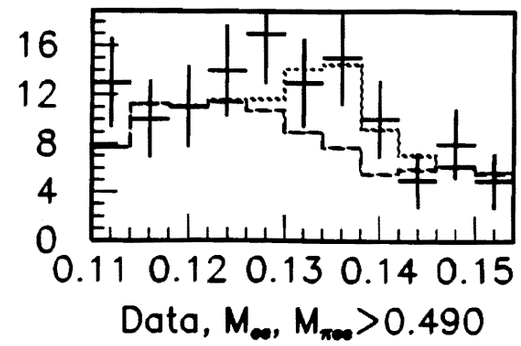

Figure 6. Reconstructed e^+e^- pair mass for events with $M_{\pi ee} > 490$ MeV from BNL E851.

$\pi^\circ \to \gamma X$

The BNL E787 experiment can also use tagged π°'s from K^+ decays to search for exotic decays. No prior limit exists for the decay $\pi^\circ \to \gamma X$, where X is a long-lived neutral non-interacting vector particle. Such a particle can arise in Standard Model extensions with an additional $U(1)$ interaction, for example, or

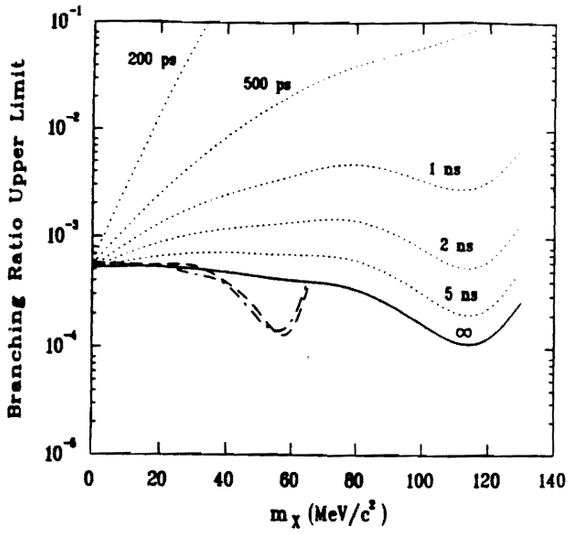

Figure 7. $B(\pi^\circ \to \gamma X)$ limits versus X mass, for different X lifetimes, from BNL E787.

in other possible scenarios. The experiment is sensitive to an X with mass below the π° mass. The experiment would also be sensitive to three body decays $\pi^\circ \to \gamma X X'$, where the X and X' could be neutrinos or supersymmetric particles. Figure 7 shows the experimental branching ratio limit as a function of the X mass. Different limits are indicated for different lifetime assumptions. The dot-dashed and dashed curves correspond to the three body scenario with a phase-space spectrum and a Dalitz-like spectrum, respectively.

FUTURE PROSPECTS

Work is now underway at both BNL and KEK to mount new rare K decay experiments. At BNL where three groups are still active, the thrust is to exploit the four-fold increase in available flux promised by the new Booster and to build on the experiences of the recently completed experiments. BNL E871 and E865 should reach the 10^{-12} level for the lepton flavor violating decays $K_L^\circ \to \mu e$ and $K^+ \to \pi^+ \mu^+ e^-$, respectively, and achieve similar sensitivities to other accessible modes. BNL E787 expects to reach an ultimate sensitivity, through beam and detector upgrades, below 10^{-10} and therefore observe $K^+ \to \pi^+ \nu \bar{\nu}$. At KEK, preparations are underway for E162, which will search for $K_L^\circ \to \pi^\circ e^+ e^-$ close to the 10^{-10} level.

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