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Rare K Decays

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1. – Theoretical Motivation

The rates for the neutral and charged versions of the flavor changing neutral current decay $K \to \pi\nu\bar{\nu}$ are dominated by terms proportional to the top to down coupling, V_{td} [1]. These decays are extremely clean theoretically, so that the relationship between the rates and fundamental input parameters is determined to $\sim 7\%$ in the charged and $< 2\%$ in the neutral case. The normally problematic hadronic matrix element is determined to good accuracy from the well-known $Ke3$ decay rate[2]. In the Wolfenstein parameterization [3] of the CKM matrix, $V_{td} = \lambda^3 A(1-\rho-i\eta)$, where η characterizes CP violation in weak decays. The charged decay mode is sensitive to both the real and imaginary components, ρ and η, while the neutral mode is sensitive only to the imaginary component, η. The contribution of indirect CP-violation to $K_L \to \pi^0\nu\bar{\nu}$ is tiny[4] and there are no significant long-distance contributions[5], so that a measurement of the neutral decay rate would yield an unambiguous determination of η, given 3-generation unitarity and knowledge of $|V_{cb}|$ (the rate is actually proportional to $[Im(V_{ts}^* V_{td})]^2$). Adding to this a measurement of $\Gamma(K^+ \to \pi^+\nu\bar{\nu})$, which is proportional to $|V_{ts}^* V_{td}|^2$ determines the unitary triangle angle β, independent of the B system[6]. Figure 1 illustrates the relationship between the unitarity triangle and the two kaon FCNC rates. The current range of prediction for $B(K^+ \to \pi^+\nu\bar{\nu})$ is $(0.6 - 1.5) \times 10^{-10}$. The magnitude of this range is almost entirely due to uncertainty in the input parameters such as $|V_{cb}|$ and $|V_{td}|$. After next-to-leading-logarithmic order QCD corrections, the intrinsic theoretical uncertainty in $|V_{td}|$, given $B(K^+ \to \pi^+\nu\bar{\nu})$, is $< 5\%$[7]. Most of this residual uncertainty is due to the charm contribution. and the rate of the neutral mode, which has no significant contribution from charm. can be calculated with an intrinsic theoretical uncertainty of < 2%. The current estimate is $B(K_L \to \pi^0 \nu\bar{\nu}) = (3 \pm 2) \times 10^{-11}$, where once again the extent of the range is given by uncertainties in the input parameters. These decays compare favorably in theoretical "hygiene" with B system measurements that have been proposed for determining the angles of the unitarity triangle

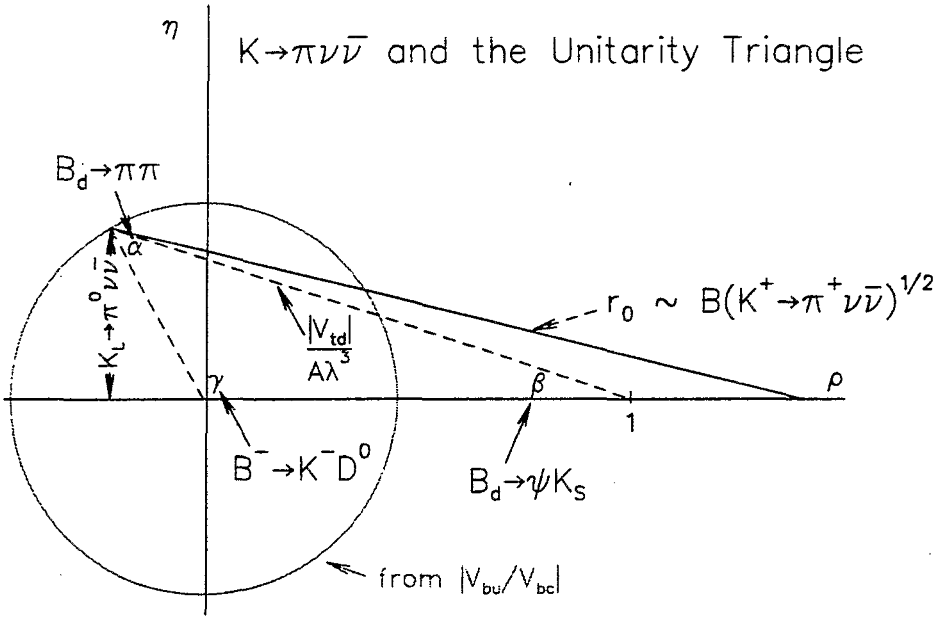

Fig. 1. – Diagram of the contribution of the charged and neutral FCNC kaon decay $K \to \pi\nu\bar{\nu}$.

2. – Status of the search for $K^+ \to \pi^+\nu\bar{\nu}$

Fig 2 shows the apparatus[8] of AGS Experiment 787 which is a solenoidal spectrometer situated at the end of a ~ 700 MeV/c separated K^+ beam. E787 has finished its third data collection run since a major beam and detector upgrade was completed in 1994. Over this period, the detector was exposed to 3.1×10^{12} kaon decays. Of those decays, 1.49×10^{12} occurred during the 1995 run. The data from that run are currently entering the last stages of analysis. The single event sensitivity obtained from the 1995 data under this analysis is 4.2×10^{-10}. The probability of any known background event passing the final cuts is calculated to be $(8 \pm 3)\%$. The collaboration expects to announce the results of the 1995 data analysis by the end of this summer (note that one event was observed[9]). With another factor of 2.5 in sensitivity recorded on tape. the E787 collaboration expects to have results from the final 95-97 data analysis by the summer of 1998, with a single event sensitivity of $\leq 1.7 \times 10^{-10}$ anticipated. We are hoping to collect at least a further factor four in sensitivity in the next couple of years. At the AGS-2000 workshop, methods for achieving yet another factor five were discussed[11]. Since the main limitation on the experiment is the instantaneous rate, one immediately applicable idea is to increase the duty factor of the AGS (currently 44%), by extending the flattop (currently 1.6 seconds every 3.6 seconds). This increases the sensitivity of the experiment proportionately, without requiring any improvement in detector performance. Another expedient is to reduce the momentum of the beam, so that a higher fraction of the incident K^+ actually stop and decay usefully in the target. This fraction is currently only about 20%. Since the rates are proportional to the K^+ striking the BeO degrader used to slow the beam, and the sensitivity is proportional to the K^+ penetrating the degrader unscathed and stopping in the target, one can clearly win in this way. Increasing the duty factor and reducing the beam momentum both require expending more of the AGS protons. Since the experiment uses only about 25% of the presently available flux, and this flux is expected to rise over the next couple of years, significant advances seem quite possible.

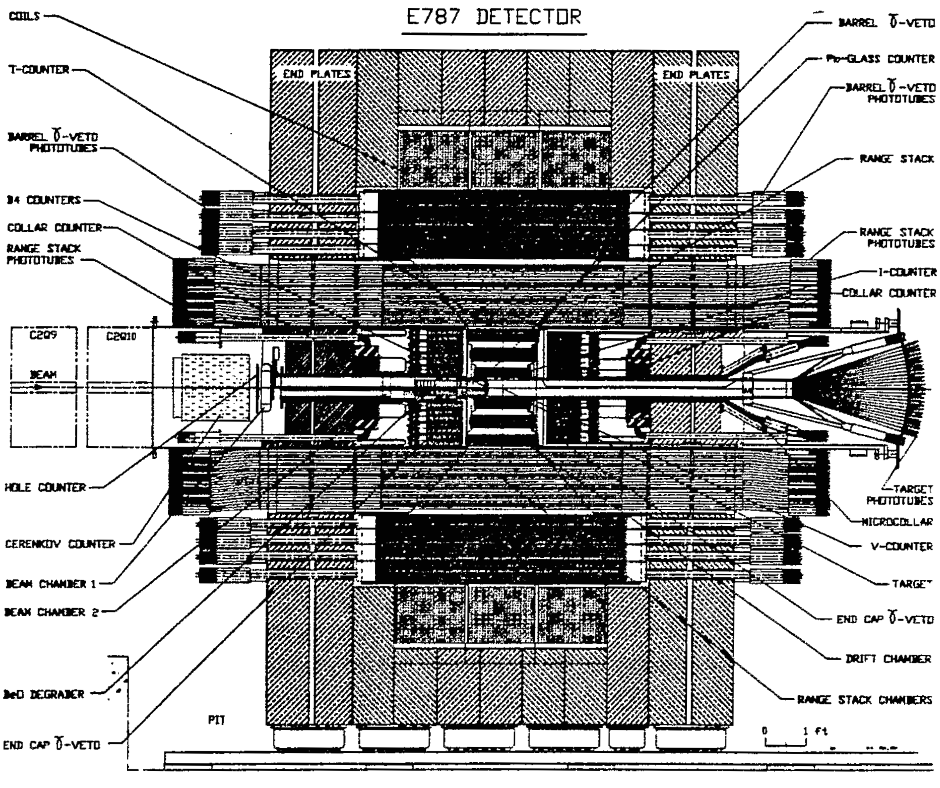

Fig. 2. – E787 detector, built into a 1-T solenoid. A $\sim$ 700 MeV/c K^+ beam enters from the left, slows down in a BeO degrader and stops in a highly-segmented scintillating fiber target. Decay π^+ are momentum analyzed by a cylindrical drift chamber and range out in an array of scintillation counters and straw chambers. A barrel lead-scintillator array and CsI (pure) endcaps complete an hermetic photon veto.

3. – Prospects for a measurement of $K^0 \to \pi^0 \nu\bar{\nu}$

With the search for charged mode decay underway for almost 10 years, attention is now turning toward designing a beam line and detector capable of measuring the neutral mode decay [10]. A schematic of the proposed detector is shown in Fig. 3. Upon the startup of the RHIC collider, the AGS will be free at least 20 hours a day for fixed target proton experiments. A program of accelerator upgrades is expected to nearly double the available proton flux by the year 2000. A set of experiments that could exploit this opportunity was recently proposed[11]. Using about half the available flux of 10^{14} protons per AGS acceleration cycle, it is estimated that in 80 weeks of running time, on the order of 70 $K^0 \to \pi^0 \nu\bar{\nu}$ events could be recorded with a background contamination of less than 10 events. This would yield a precision on η of $< 10\%$ (modulo uncertainty in CKM A). The techniques for attaining the needed sensitivity and background rejection are as follows. First the neutral beam will be extracted at a very wide angle ($\sim 45^o$) to soften both the neutron and kaon momentum spectra. This minimizes the flux of neutrons above π^0 production threshold, which are the ones that can produce background by interacting with vacuum windows or residual gas. To further suppress background from the latter, a vacuum of 10^{-7} Torr must be maintained throughout the beam region. Second, the proton beam from the AGS will be bunched upon extraction to have a time microstructure with a period of about 40ns. The rms bunch width will be ≤ 200 ps in order to allow the use of time of flight measurement to determine the neutral kaon's momentum to a few percent. The soft kaon spectrum ($\bar{p} \sim 750$MeV/c) facilitates this. Also, with this time bunching technique, the massless and other fast debris from the target interaction will arrive at the detector before the kaons of interest, and so can be distinguished from the latters' decay products. Third, the detector will incorporate active shower pre-converters which allow measurement of the direction of the π^0 photons coming from the $K_L \to \pi^0 \nu\bar{\nu}$ decay. In conjunction with a high resolution scintillating fiber calorimeter, this allows one to fully reconstruct the π^0, independent of any assumptions about the beam. Finally, combining this with the beam timing information, one can transform the π^0 into the K_L center of mass. The last major requirement is hermetic photon vetoing. Extrapolating from photon vetoing performance measured in E787, it is estimated that an average single γ rejection of $10^4 : 1$ can be achieved. The main expected background to $K_L \to \pi^0 \nu\bar{\nu}$ is the 300-million-fold more frequent $K_L \to \pi^0\pi^0$ decay ($K_{\pi 2}$). These events become background when two of the four final state photons are missed. If the two missing photons are from the decay of the same π^0 ("even" case), then the two detected will reconstruct properly to a π^0 meson. The energy of this reconstructed π^0, in the rest frame of the K_L, will equal 248.84 MeV/c (smeared by the resolution). If the two detected photons each originate from a different π^0 ("odd" case), then they will not, in general, reconstruct to a π^0 mass. In addition, the $K_{\pi 2}$ events which evade the photon veto tend to have rather small values of missing energy and missing mass compared to signal events. Therefore, with proper kinematic cuts, one is able to suppress this $K_{\pi 2}$ background to $\leq 10\%$ of the signal.

Other potential backgrounds sources are $K_L \to \gamma\gamma$, $K_L \to \pi^- e^+ \nu$, with the e^+

annihilating and the π^- undergoing charge exchange before they are detected, $\Lambda \to \pi^0 n$, and accidentals. These backgrounds have been calculated to contribute each to less than 1 event after 80 weeks of AGS 2000 running time.

The E926 proposal received scientific approval by the AGS PAC in October, 1996.

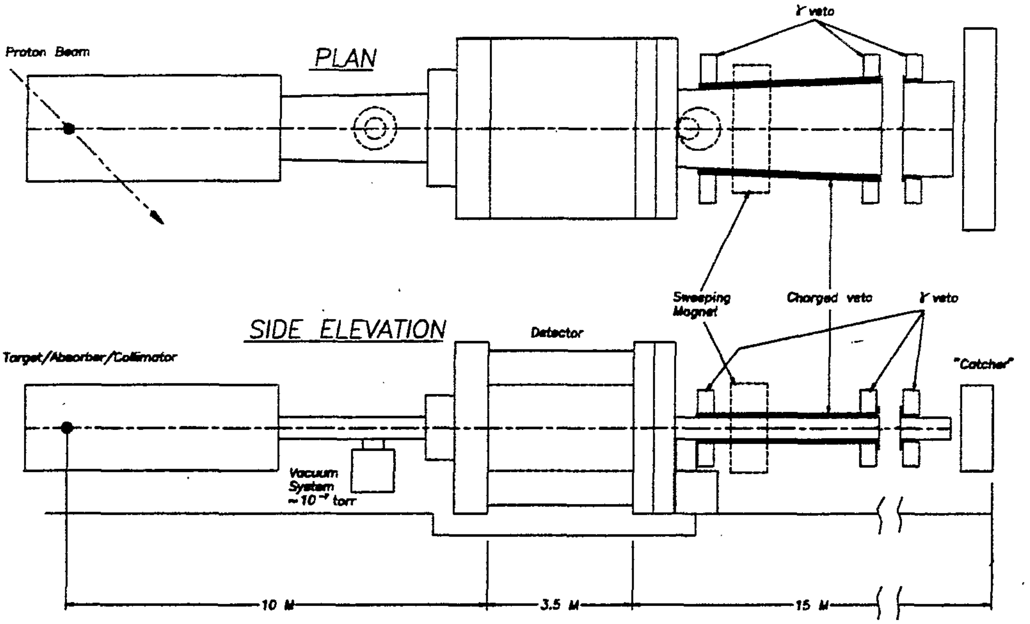

Fig. 3. – Schematic of the proposed 926 detector.

4. – Conclusion

In the rush to explore the B system, one should not ignore the potential of rare K decays. The charged and neutral FCNC $K \to \pi\nu\bar{\nu}$ decays are theoretically very clean, on a par with $B \to \psi K_S$, which measures β, and much less problematic than $B \to \pi\pi$ and $B_s \to K^+K^-$ or $B_s \to K^{*+}K^{*-}$ which have been proposed to measure α and γ respectively. $B(K^+ \to \pi^+\nu\bar{\nu})$, which in the Standard Model yields information on $|V_{ts}^* V_{td}|$, is closely related to the ratio of $B_d - \bar{B}_d$ to $B_s - \bar{B}_s$ mixing, which yields $|V_{td}/V_{ts}|$. It is essential to compare such clean measurements from the B and K sectors, because new physics is likely to manifest itself in apparent disagreements[12].

Measuring the branching ratios of $K \to \pi\nu\bar{\nu}$ decays is a challenge, but the current proven reach in sensitivity for the charged mode and the prospect of measuring the neutral mode at AGS-2000 indicate that this window into flavor physics is on the verge of becoming an exploitable reality.

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