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E787: A Search for the Rare Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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ABSTRACT

Recent results from the first phase of the E787 experiment and an update on the current status are presented. From the first phase the limit on the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio is $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 2.4 \times 10^{-9}$. An observation of the decay $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ has been made using two separate techniques. An observation of the decay $K^+ \rightarrow \pi^+ \gamma \gamma$ has been made and the distribution of two photon invariant mass is inconsistent with phase space but consistent with chiral perturbation theory.

A description of recent upgrades to the detector follows. With the upgraded detector the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay should soon be observable. A discussion of the expected sensitivity for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ during the current running period is presented. Possible improvements, in order to make a significant measurement of $|V_{td}|$, are discussed. One result from the upgraded detector is a measurement of the structure dependent part (SD^+) of the decay $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ with a branching ratio of $\text{BR}(\text{SD}^+) = (1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$.

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1 Introduction

The rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is a flavor changing neutral current, mediated in the standard model by heavy quark loop diagrams, and in particular, is sensitive to the CKM matrix element $|V_{td}|$. The theoretical prediction for this branching ratio is

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very clean: the hadronic matrix element can be determined from the $K^+ \rightarrow \pi^0 e^+ \nu_e$ branching ratio via an isospin transformation, the long distance contributions are negligible, and the QCD corrections have been calculated to next to leading log; bringing the theoretical uncertainty to 7%¹⁾).

The standard model prediction for the branching ratio is $\sim 1 \times 10^{-10}$. Due to the current uncertainty in V_{td} , m_t , and V_{cb} a value for the branching ratio outside of the range $0.6 - 3.0 \times 10^{-10}$ would be unexpected. Over the next few years the E787 experiment at the AGS is expected to reach a single event sensitivity of a few $\times 10^{-11}$ and should therefore observe $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.

2 The early experimental results

The early version of the detector is described elsewhere²⁾, but a schematic of the upgraded version shows essentially the same functionality (see Fig.1). An 800 MeV/c

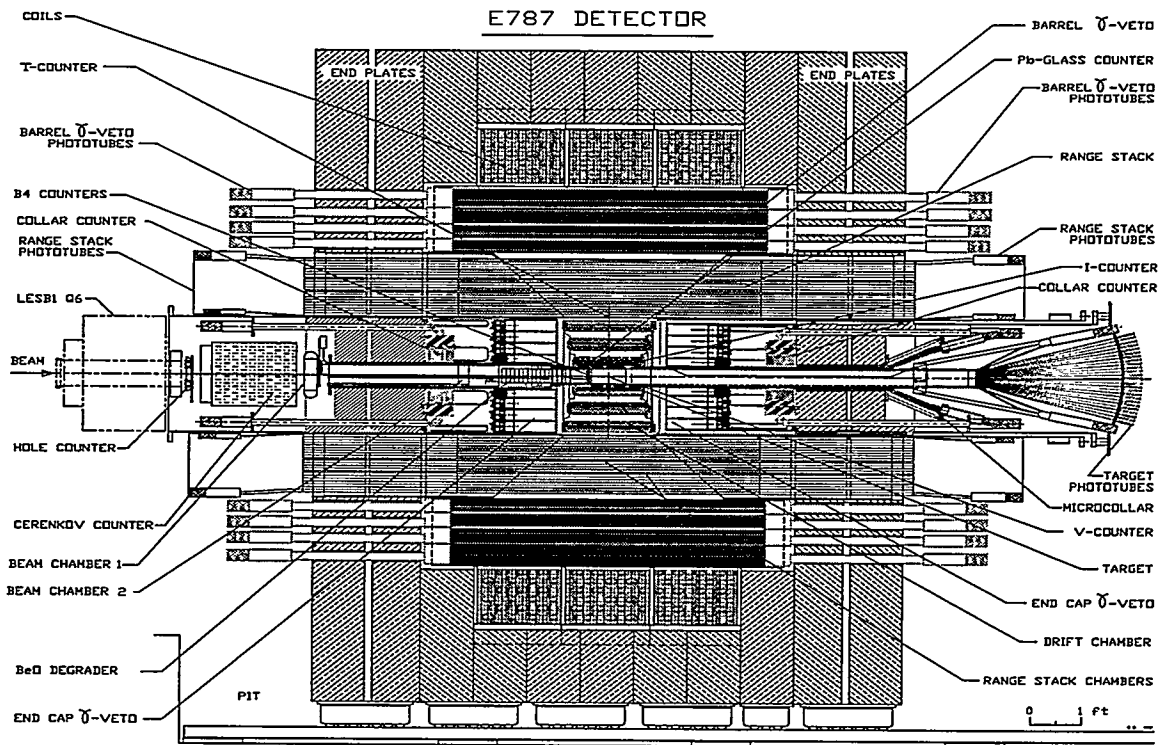


Figure 1: *The E787 Detector.*

K^+ beam, incident from the left, is stopped in a scintillating fiber target in the center of the 10kG solenoidal magnet field.

The experimental signature for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is a single charged kaon track incident and a single charged pion track outgoing, with two missing neutrinos. Given

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the weak constraints and the small branching ratio, the particle identification and kinematics of the π must be very well measured and any additional particles must be vetoed with high efficiency. This is most readily solved in the center of mass frame; therefore, E787 runs in a stopped kaon beam at the AGS. The two dominant decay modes, $K_{\pi 2}$ and $K_{\mu 2}$, produce mono-energetic charged particles which can be kinematically separated from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. The E787 detector uses redundant measures of the kinematics: momentum, energy and range. The $K_{\pi 2}$ can also be suppressed by vetoing on the π^0 photons, so the detector is surrounded by a nearly 4π photon veto (PV) and in fact almost the entire detector not traversed by the π^+ is used as a veto. The $K_{\mu 2}$ can be suppressed by requiring that the π decay to a μ in the range stack (RS). The entire $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain is observed with 500 MHz, 8-bit transient digitizers (TD) sampling the output of the RS scintillators. The next significant background comes from scattered beam pions. The primary tools for rejecting these events are fast, finely segmented beam counters and good tracking in the fiber target.

2.1 Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

A significant $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data set was collected with the original detector during the period from 1989–1991. The analysis of this data is described in detail elsewhere.³⁾ A total of 3.49×10^{11} kaons were stopped (KB_L). A final plot of the range and kinetic energy of events remaining after all cuts is shown in Fig.2. No

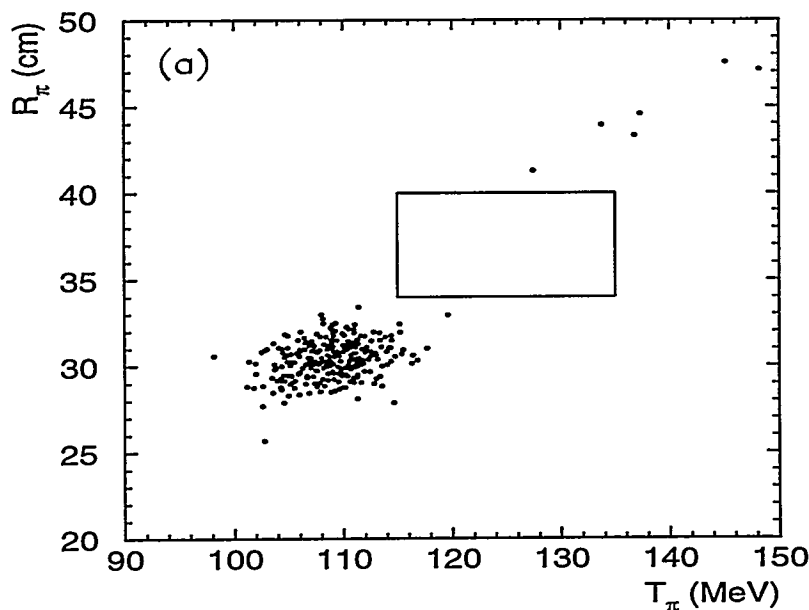


Figure 2: *Distribution of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates after all cuts.*

events were seen, implying a 90% CL limit on the branching ratio of:

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 2.4 \times 10^{-9}$$

$$BR(K^+ \rightarrow \pi^+ X^0) < 5.2 \times 10^{-10}$$

2.2 Observation of the decay $K^+ \rightarrow \pi^+ \mu^+ \mu^-$

A sample of 6×10^6 $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ candidates was collected during the 1989–91 running period ($KB_L = 3.03 \times 10^{11}$).⁴⁾ The $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ trigger required two charged tracks to reach the range stack, but not to penetrate very deeply, and required that there be no activity in the PV. A total of 6×10^6 triggers was collected during 1989–91. Two separate techniques of analyzing the data were employed. One analysis required that all three tracks be reconstructed in the drift chamber. A second analysis, with larger acceptance, did not require that the 3rd be fully reconstructed. If the 3rd track remains in the target no momentum information is available, but the total kinetic energy (Q) is. Figure 3 shows the final samples. The

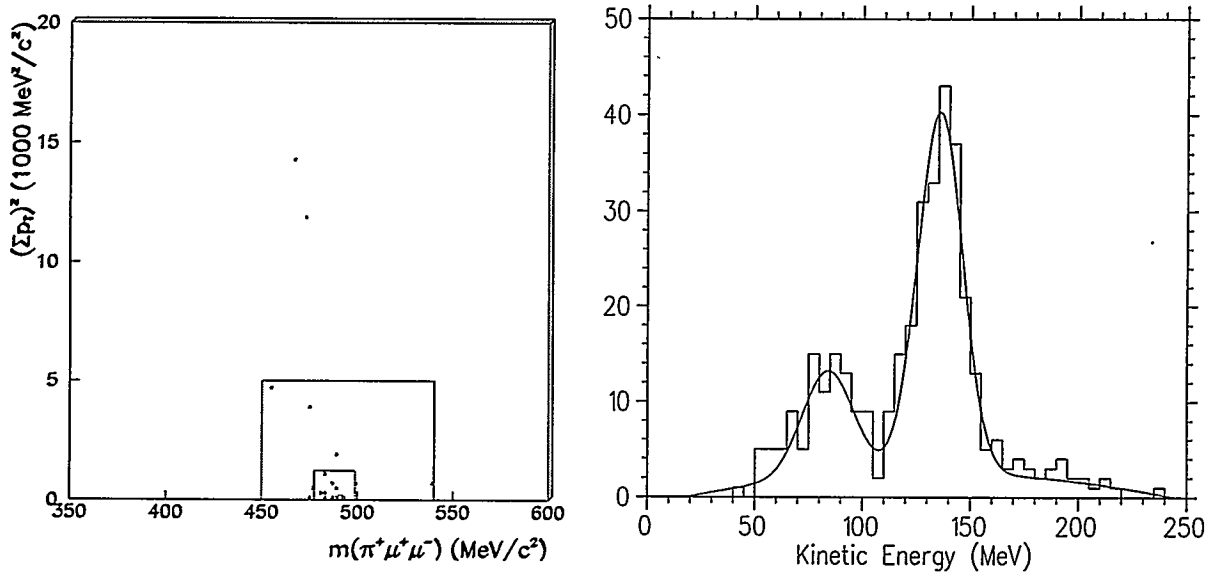


Figure 3: *Final plots for $K^+ \rightarrow \pi^+ \mu^+ \mu^-$.*

left figure shows the events that survive all cuts of the first analysis as a scatter plot of the reconstructed kaon mass vs. the square of the transverse momentum. A total of 13 events were seen in the small signal box, at low p_T^2 and M_K . The larger box (excluding the smaller one) is used for a background estimation. It is dominated by K_{e4} that have passed the 90% confidence level electron rejection cut. The background estimate is 2.5 ± 1.1 events in the signal box. The plot on the right

shows the kinetic energy of the final sample of events from the second analysis. In this case we see a clear peak at the value of $Q = 143$ MeV from the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay, as well as a smaller peak at $Q = 75$ from the $K_{\pi 3}$ decay. A fit to the signal plus background yields 196.0 ± 16.7 signal events.

2.3 Observation of the $K^+ \rightarrow \pi^+ \gamma \gamma$ decay

A total of 2.7×10^6 $K^+ \rightarrow \pi^+ \gamma \gamma$ triggers were collected ($KB_L = 1.01 \times 10^{10}$) during the 1991 run. ⁵⁾ The trigger selected π^+ with short range and di-photons with an opening angle $> \sim 90^\circ$ and an invariant mass between 190–600 MeV/c². The major backgrounds are from two classes. The first is $K_{\pi 3}$ and $K_{\pi 2 \gamma}$ with overlapping photons. These are rejected by cuts targeting the ϕ and z consistency of the photon clusters. The second class includes $K_{\mu 3}$, $K_{\pi 2}$, $K_{\pi 3}$ and $K_{\pi 2 \gamma}$; these are all kinematically distinct from $K^+ \rightarrow \pi^+ \gamma \gamma$. The $K_{\mu 3}$'s are missing a neutrino and the μ must be misidentified as a π . The π in $K_{\pi 2}$ must scatter in the target and be down-shifted in momentum. The $K_{\pi 3}$ and $K_{\pi 2 \gamma}$ are missing a photon and do not conserve momentum. After all cuts targeting these backgrounds are applied, 31 events survive. After a background subtraction, the signal is 26.4 ± 6.2 events. A plot of $M_{\gamma \gamma}$ of the remaining events is shown in Fig.4 The distribution is significantly different than phase space and is consistent with Chiral Perturbation Theory (χ PT).

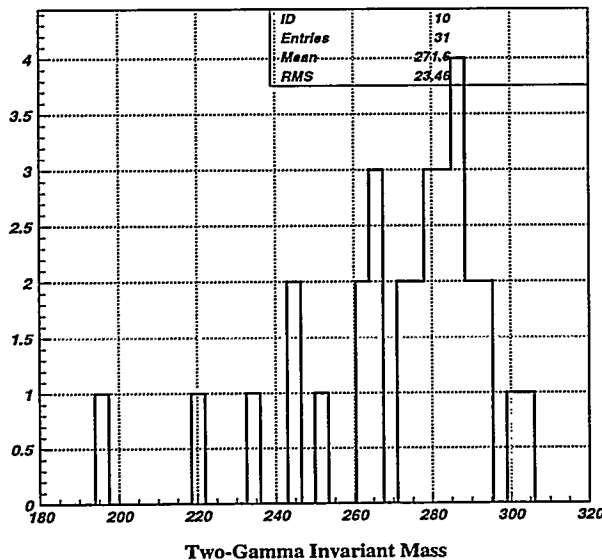


Figure 4: *Fitted $M_{\gamma \gamma}$ of events surviving cuts.*

A second sample of $K^+ \rightarrow \pi^+ \gamma \gamma$ with a long range pion and a low $M_{\gamma \gamma}$ found no events and set a limit of $BR(K^+ \rightarrow \pi^+ \gamma \gamma, |p_\pi| < 217 \text{ MeV}/c) < 5.1 \times 10^{-7}$,

assuming a phase space distribution. A small branching ratio for $|p_\pi| < 217$ MeV/c is consistent with χ PT.

3 The Current Status of E787

Following the 1991 run a number of upgrades to the E787 experiment were undertaken. With the increased proton intensity available from the AGS with the Booster, the beam line and essentially every detector system were upgraded to handle higher rates and to maintain and improve the background rejection. A drawing of the upgraded E787 detector is shown in Fig.1

3.1 Upgrades

The first of these was the construction of a new low energy separated K^+ beam-line (LESB3).⁶⁾ The central drift chamber was replaced with a new ultra-thin chamber (UTC). The momentum resolution for $K_{\pi 2}$ and $K_{\mu 2}$ of 1.2% and the z resolution of 1 mm are both improved by $\times 2$ compared to the previous drift chamber.⁷⁾ The Pb-scintillator endcaps (EC) were replaced with pure CsI crystals. The timing resolution is improved by $\times 2-3$; with $\sigma_T \sim 600$ ps for γ 's with $E > 20$ MeV.⁸⁾ The EC was moved closed to the UTC to increase the coverage at the thinner corners at $\sim 45^\circ$. Additional Pb-scintillator photon veto systems were installed behind the endcap: the collar (CO) and micro-collar (CM). The RS signals were more finely segmented, with a PMT on each end of each scintillator. This provides better dE/dx resolution and more light ($\times 1.3$ p.e.). The tracking chambers within the RS were replaced with very low mass straw chambers (RSSC). The target was replaced with a much brighter scintillating fiber target (TT). Tests of the new fibers show $\times 4-5$ more light (20 p.e./MeV , $L_{atten} = 2$ m). An additional beam chamber was added, (BWPC2). A new Čerenkov (C_K and C_π) counter with more light collection was installed. A new transient digitizing system based on GAs CCD's sampling with 8 bits at 500 MHz was instrumented on the EC, TT and beam elements with ranges of 512 ns, 256ns, 256 ns respectively.⁹⁾ A new Fastbus based trigger, including a fast L1.1 trigger, was built. The L1.1 is based in an ASIC on the TD¹⁰⁾ boards and makes a pulse area to pulse height comparison to reject 90-95% of μ^+ in 10-20 μ sec. The data acquisition system was upgraded to RISC based processors¹¹⁾ (12 CPU SGI Challenge) with a specially built VME to Fastbus interface¹²⁾. The system is consistently able to sustain an upload of 24 Mbytes in the 2 seconds between spills.

3.2 $K^+ \rightarrow \mu^+ \nu_\mu \gamma$

The internal bremsstrahlung component (IB) of $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ has been well measured. ¹³⁾ However, the structure dependent part, SD^+ and SD^- , (γ radiated from internal hadron lines) had never been observed. A two day period of data taking in 1994 ($KB_L = 9.2 \times 10^9$) was dedicated to a measurement of SD^+ , which has an energetic μ and an energetic γ . ¹⁴⁾

The primary backgrounds are $K_{\pi 2}$ and $K_{\mu 3}$ with a missed γ and $K_{\mu 2}$ with an accidental γ . These are suppressed by requiring the μ^+ momentum to be above the $K^+ \rightarrow \pi^0 \mu^+ \nu_e$ endpoint of 215 MeV/c, by vetoing on additional photons, and by requiring that the kinematics are consistent with $K^+ \rightarrow \mu^+ \nu_\mu \gamma$. After all cuts the background was reduced to 105 ± 6 events out of 2693 in the signal region. A fit to the background, IB, SD^+ SD^- and interference components yields a branching ratio:

$$BR(SD^+) = (1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$$

which gives a determination of the form factor $|F_V + F_A| = 0.165 \pm 0.007 \pm 0.011$. The $O(p^4)$ χ PT prediction for the branching ratio is $BR(SD^+) = 9.2 \times 10^{-6}$. ¹⁵⁾

As a check, a measurement of the Inner Bremsstrahlung component of $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ gives $BR(IB) = (3.57 \pm 0.27) \times 10^{-4}$, which can be compared to the theoretical value $BR(IB, E_\mu > 100 MeV, E_\gamma > 20 MeV) = 3.30 \times 10^{-4}$.

3.3 Expected Sensitivity for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

A commissioning run with most of the new detector in 1994 produced new results on $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ and provided a shakedown of most of the new detector. The two modestly long running periods in 1995 and 1996 (24 and 17 weeks) have provided a significant $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data sample. The accumulated number of stopped kaons were 1.55×10^{12} and 1.15×10^{12} respectively. Preliminary studies indicate that the backgrounds can be kept to the 10^{-11} level with acceptances comparable to the previous years.

4 Future Plans

During the recent AGS2000 workshop a plan for making a 20% measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio (10% measurement of $|V_{td}|$) was outlined. ¹⁶⁾ The plan envisioned a factor of 10 increase in sensitivity per year (allowing an observation of several events per year). In order to make solid extrapolations of acceptance and background rejection, no significant increases in rates are planned. The major

improvement factors come from reducing the beam momentum (and increasing the fraction of usable kaons that stop in the target) and from increasing the duty factor of the AGS. Such a plan, with modest upgrades to the E787 experiment would allow the CKM model of CP violation to be critically tested.

A history of the limits on the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio is shown in Fig.5 for measurements through 1991, with some extrapolations to the near future, and

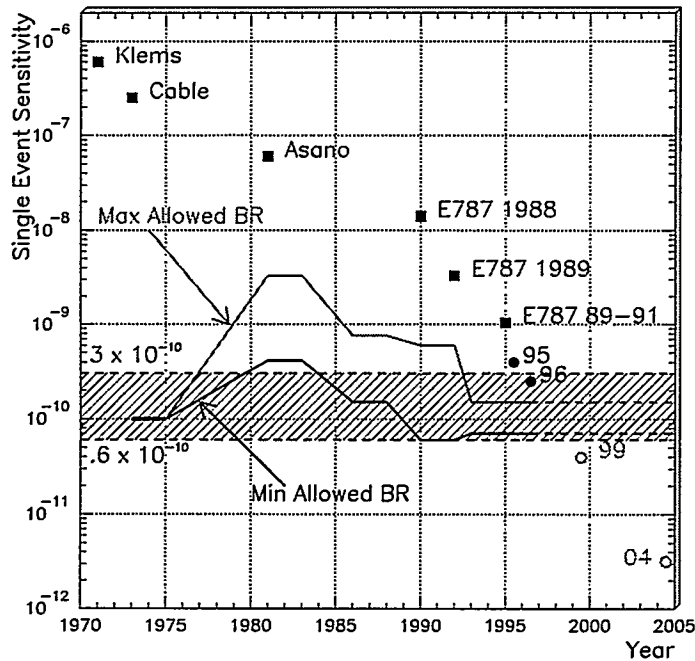


Figure 5: *Past and Future Progress in searching for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.*

some estimates of what could be done in the AGS2000 era. The curves show the evolution of the theoretical predictions over time.

5 Conclusions

The E787 experiment has reached a very exciting time, as the sensitivity of the experiment is now very close to the standard model prediction for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and the experiment should expect to see events soon.

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