STATUS OF THE STUDY OF THE RARE DECAY
$K^+ \to \pi^+ \nu \bar{\nu}$ AT BNL

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The current status of the experimental study of the rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ at Brookhaven National Laboratory (BNL) by the E787 and E949 collaborations is reported.

1 Theoretical Motivation

The $K^+ \to \pi^+ \nu \bar{\nu}$ decay is a flavor changing neutral current process induced in the Standard Model (SM) by loop effects in the form of penguin and box diagrams. The decay is sensitive to top-quark effects and provides an excellent route to determine the absolute value of $V_{td}$ in the Cabibbo-Kobayashi-Maskawa matrix. Long-distance contributions are negligible and the hadronic matrix element is extracted from the $K^+ \to \pi^0 e^+ \nu$ decay. The theoretical uncertainty is 7% from the charm-quark contribution in the next-to-leading-logarithmic QCD calculations.

The branching ratio is represented in the SM as:

$$
B(K^+ \to \pi^+ \nu \bar{\nu}) = 4.57 \times 10^{-11} \times A^4 \times X(x_t)^2 \times \left[ (\rho_0 - \rho)^2 + \eta^2 \right]
$$

in the Wolfenstein parameterization $A$, $\rho$ and $\eta$. With the $\rho$-$\eta$ constraints from other K and B decay experiments, the SM prediction of the branching ratio is $(0.6 - 1.5) \times 10^{-10}$. New physics beyond the SM could affect the branching ratio. In addition, the two-body decay $K^+ \to \pi^+ X^0$, where the $X^0$ is a weakly-interacting light particle such as a familon, could also be observed as a $\pi^+$ plus nothing decay. Since the effects of new physics are not expected to be too large, a precise measurement of a decay at the level of $10^{-10}$ is required.

2 E787 Detector and Analysis

Experiment 787 at the Alternating Gradient Synchrotron (AGS) of BNL performed an initial search in 1989-91 and obtained the 90% confidence level

$B(X(x_t))$ is the Inami-Lim loop function with the QCD correction, $x_t = m_t^2/m_W^2$, and $\rho_0$ is due to the charm contribution.

$E787$ is a collaboration of BNL, Fukui, KEK, Osaka, Princeton, TRIUMF and Alberta.
upper limit of $2.4 \times 10^{-9}$. Following major upgrades of the detector and the beam line, E787 took data from 1995 to 1998.

E787 measures the charged track emanating from stopped $K^+$ decays. The $\pi^+$ momentum from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is less than 227 MeV/c as shown in Figure 1, while the major background sources of $K^+ \rightarrow \pi^+ \pi^0$ ($K\pi^2$, 21.2%) and $K^+ \rightarrow \mu^+ \nu$ ($K\mu_2$, 63.5%) are two-body decays and have monochromatic momentum of 205 MeV/c and 236 MeV/c, respectively. The region “above the $K\pi^2$” between 211 MeV/c and 230 MeV/c is adopted for the search.

The E787 detector (Figure 2) is a solenoidal spectrometer with the 1.0 Tesla field directed along the beam line. Slowed by a BeO degrader, kaons stop in the scintillating-fiber target at the center of the detector. A delayed coincidence requirement (> 2 nsec) of the timing between the stopping kaon and the outgoing pion helps to reject backgrounds of pions scattered into the detector or kaons decaying in flight. Charged decay products pass through the drift chamber, lose energy by ionization loss and stop in the Range Stack made of plastic scintillators and straw chambers. Momentum, kinetic energy and range are measured to reject the backgrounds by kinematic requirements. For further rejection of $\mu^+$ tracks, the output pulse-shapes of the Range Stack counters are recorded and analyzed so that the decay chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ is identified in the stopping scintillator. $K\pi_2$ and other decay modes with extra particles ($\gamma$, $e$, ...) are vetoed by the in-time signals in the hermetic shower counters.

Extremely effective background suppression is required in this experiment,
and reliable estimation of the rejections is essential to interpret potential observations. Data rather than Monte Carlo are used to do background studies. A set of background samples is prepared by reversing some of the selection cuts \( c \), which also assures that the development of the cuts and estimates of the background levels are made without looking at the candidate events ("blind" analysis). Furthermore, background studies are performed with partial data samples and the results are confirmed using the full sample. Possible correlations of the cuts are investigated. The background levels around the signal region are predicted by loosening cuts and are confirmed using data. Background level shapes inside the signal region are calculated in advance in the form of likelihood functions.

In the 1995 data set, with the total kaons stopping in the target \( 1.49 \times 10^{12} \) and the acceptance \( 0.16\% \), one event, shown in Figure 3, was observed in the signal region. The estimated background level (0.08 ± 0.03 events) corresponds to a branching ratio of \( 3 \times 10^{-11} \). The measured branching ratio is \( (4.2^{+9.7}_{-3.5}) \times 10^{-10} \) (0.006 < \( |V_{td}| < 0.06 \)), which is consistent with the SM prediction.

\footnote{For example: the \( K_{e2} \) backgrounds are rejected by kinematic cuts and photon veto cuts. By reversing the veto and requiring photons from \( \pi^0 \) in the detector, the tails in the \( \pi^+ \) kinematic distributions are studied. By picking up events with the track momentum/energy/range in the \( K_{e2} \) peak and by applying the photon veto cuts, the rejection of the veto is checked.}
3 E787 in 1996, 97 and 98

The total acceptance of 0.16% includes the phase space above the $K_{\pi 2}$ (0.16), solid angle acceptance of the charged track (0.39), $\pi^+$ stop without nuclear interaction nor decay-in-flight in the detector (0.50), and the acceptance of $\pi^+$ identification with the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain (0.25) to achieve the $\mu^+$ rejection of $10^5$. The main limitation due to the requirement of no extra hits in the detector at the decay time is applied in the analysis costing around 40% of the acceptance. The strategy of E787 for the post-1995 runs was therefore to limit the instantaneous rates and attempt to gain in the overall number of stopped kaons.

In the experiment, only 20% of the kaons in the beam are slowed down and stop in the target while the remainder are lost or scattered out in the degrader. The rates in the E787 detector are proportional to the incident kaons, not to the stopped kaons in the target. That means, with the same incident flux and a lower beam-momentum, the kaon stopping fraction increases while accidental hits decrease. Also, using additional proton intensity to extend the spill length without increasing the instantaneous rate raises the number of kaon decays per hour without impacting the acceptance.

By reducing the beam-momentum from 790MeV/c in 1995 to 710MeV/c in 1997 the fraction of incident kaons stopping in the target was improved by 44%. The AGS spill length was extended from 1.6sec to 2.2sec in 1998. Other improvements in the trigger and readout provide acceptance gains of about 20%. In the off-line analysis, kinematic codes with better resolution and rejection-power were developed, and in the current study of the combined 1995-97 data sets more rejection corresponding to the background level of $1 \times 10^{-11}$
has been achieved with minimal loss in acceptance. The analysis is ongoing.
The expected sensitivity for the the entire E787 data should reach less than
$0.9 \times 10^{-10}$.

4 The New E949 Experiment

From 1999 the Relativistic Heavy Ion Collider (RHIC) at BNL starts operation,
and the AGS is primarily used as the RHIC injector. However it is required
for only $\sim 4$ hours per day for this purpose. The rest of the time can be
used for the proton program. The new experiment 949 is to continue the
experimental study of $K^+ \to \pi^+ \nu \bar{\nu}$ at the AGS based on the E787 experience.
An additional photon veto system will be installed in the detector to improve
the photon rejection. E949 aims to reach a sensitivity of $10^{-11}$ or less in two
to three years of operation.

5 Summary

E787 has observed the evidence for the $K^+ \to \pi^+ \nu \bar{\nu}$ decay in the 1995 data
set and, with the entire data through 1998, expects to reach the sensitivity
better than $0.9 \times 10^{-10}$. The new E949 continues the study at the BNL-AGS.

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d E949 is a collaboration of Alberta, BNL, Fukui, INR, KEK, Osaka and TRIUMF. The
information is available at [http://www.phy.bnl.gov/e949](http://www.phy.bnl.gov/e949).