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E949 $\mathbf{K^+ \to \pi^+ \nu \bar{\nu}}$ Results

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ABSTRACT
The recent results on $K^+ \to \pi^+ \nu \bar{\nu}$ from Brookhaven experiment E949 are presented.

The decay $K^+ \to \pi^+ \nu \bar{\nu}$ is one of a handful of processes that offer clear and unambiguous information on the CKM unitarity triangle [1]. Specifically, the rate of charged kaon decay to the $\pi \nu \bar{\nu}$ final state is governed by flavor-changing neutral currents in the standard model (SM) and is proportional to the squared of the CKM matrix element $V_{\rm td}$ with an uncertainty of $\sim 5\%$ due to a mild dependence on the charm quark mass [2]. Precision measurement of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ along with the corresponding neutral kaon decay $\mathcal{B}(K^0_L \to \pi^0 \nu \bar{\nu})$ suffice to determine the apex of the CKM unitarity triangle. Indeed, a comparison of $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})/\mathcal{B}(K^0_L \to \pi^0 \nu \bar{\nu})$ with the time-dependent asymmetry of $B^0 \to J/\psi K^0_S$ decays is perhaps the definitive test of the SM description of CP violation [1].

Given the current knowledge of the CKM matrix elements and their uncertainties, $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$ is expected to be $(0.78 \pm 0.12) \times 10^{-10}$. This extremely low rate, coupled with the lack of a distinctive kinematic signature, makes observation of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ an experimental challenge. Experiment E787 at Brookhaven National Laboratory (BNL) has observed two candidates for the decay $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ upon an estimated background of 0.15 ± 0.04 events in the kinematic region between the copious two-body decays $\mathrm{K}^+ \to \pi^+\pi^0$ and $\mathrm{K}^+ \to \mu^+\nu$ dubbed "pnn1". If these candidates are interpreted as $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ decays, the corresponding branching fraction is $(1.57^{+1.75}_{-0.82}) \times 10^{-10}$ and is statistically consistent with the SM expectation but with a central value that two times higher than expected [3].

Experiment E949 was approved in 1999 as an extensive upgrade of E787 with the goal of observing 5-10 $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ events. E949 accumulated 1.8×10^{12} stopped K^+ in the spring of 2002 before high energy physics running at the BNL Alternating Gradient Synchrotron (AGS) was halted. The 12 weeks corresponds to approximately one-fifth of the approved running and E949 is seeking additional funding to complete the experiment. The results of the 2002 run in the pnn1 kinematic region are the subject of this report.

As alluded to earlier, $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$ is an experimental challenge because of its low rate and kinematic signature. It is a three-body final state with only one observable particle. Table 1 contrasts the expected rate of this decay with known processes quantitatively illustrating the need of enormous background suppression. The backgrounds can be classified into four groups:

1. $\mathrm{K}^+ \to \pi^+\pi^0$ ($K_{\pi 2}$),
2. K^+ decays with a muon in the final state including $\mathrm{K}^+ \to \mu^+\nu$ ($K_{\mu 2}$), $\mathrm{K}^+ \to \mu^+\nu\gamma$, $\mathrm{K}^+ \to \mu^+\nu\pi^0$ and $\mathrm{K}^+ \to \pi^+\pi^0$ with π^+ decay-in-flight, (the latter three components are referred to as $K_{\mu m}$),
3. beam backgrounds when a π^+ from the beam scatters in the target into the detector and
4. the charge-exchange (CEX) process $\mathrm{K}^+ n \to \mathrm{K}^0 X$, $\mathrm{K}^0 \to \mathrm{K}^0_\mathrm{L}$, $\mathrm{K}^0_\mathrm{L} \to \pi^+\ell^-\nu$ with $\ell = \mu$ or e.

E949, like its predecessor E787, operates in a low-energy separated beam with a nominal K^+/π^+ rate of 4 at a momentum of ~ 700 MeV/c [4]. The

Table 1: *The rates of background processes to* $K^+ \rightarrow \pi^+\nu\bar{\nu}$*. CEX* $\equiv(K^+n \rightarrow K^0X)\times(K^0 \rightarrow K^0_L) \times (K^0_L \rightarrow \pi^+\ell^-\nu)$*.* ℓ^- *is* μ^- *or* e^-*. The* $K^+n \rightarrow K^0X$ *rate is empirically determined.*

Process	Rate
$K^+ \rightarrow \pi^+\nu\bar{\nu}$	0.78×10^{-10}
$K^+ \rightarrow \pi^+\pi^0$	$2113000000.00 \times 10^{-10}$
$K^+ \rightarrow \mu^+\nu$	$6343000000.00 \times 10^{-10}$
$K^+ \rightarrow \mu^+\nu\gamma$	$55000000.00 \times 10^{-10}$
$K^+ \rightarrow \pi^0\mu^+\nu$	$327000000.00 \times 10^{-10}$
CEX	$\sim 46000.00 \times 10^{-10}$
Scattered π^+ beam	$\sim 25000000.00 \times 10^{-10}$

charged beam is directed along the axis of a 1T solenoid and through Cherenkov detectors and wire chambers, slowed in BeO and an active degrader and stopped in a scintillating fiber target. The trigger accepts K^+ decays after a delay of ~ 2 ns with an outgoing charged particle that traverses a low-mass drift chamber and stops in a cylindrical range stack (RS) of 2 cm thick layers of plastic scintillator. The RS is instrumented with 500 MHz transient digitizers that permit observation of the $\pi \rightarrow \mu \rightarrow e$ decay chain for positive π^+ identification. The RS is surrounded by lead/scintillator sandwich-style detectors for photon detection. Endcaps of pure CsI crystals and other lead/scintillator detectors in the beam region comprise the remainder of the photon detectors.

E949 relies on two independent methods of rejection of each of the four background processes in order to measure the level of suppression with the data as well as achieve the necessary level of background. As an example, $K^+ \rightarrow \pi^+\pi^0$ decays are suppressed by measurement of the π^+ kinematic quantities energy (E), momentum (P) and range (R) in plastic scintillator and by detection of photons from π^0 decay. Inversion of the criteria ("cuts") of each method enhances the background and permits a measurement of the background rejection of the complementary cut with the data. To confirm the background estimate with this method, the rate of events outside the predetermined signal region is compared with the prediction as the two complementary cuts are loosened simultaneously to accept background rates hundreds of times that expected in the signal region. The results of this procedure for the $K^+ \rightarrow \pi^+\pi^0$ and $K^+ \rightarrow \mu^+X$ backgrounds show good agreement between

Table 2: *The fitted constants c of the ratios of the observed to the predicted numbers of background events and the probability of* χ^2 *of the fits for the two-body backgrounds,* $K_{\pi 2}$*,* $K_{\mu 2}$ *and and multi-body* $K_{\mu m}$ *backgrounds near but outside the signal region. The first uncertainty in c was due to the statistics of the observed events and the second was due to the uncertainty in the predicted rate. The predicted numbers of background events within the signal region and their statistical uncertainties are also tabulated in the fourth column. Other backgrounds contributed an additional* 0.014 ± 0.003 *events resulting in a total number of background events expected in the signal region of* 0.30 ± 0.03.

Background	c	χ^2 Probability	Events
$K_{\pi 2}$	$0.85 \; ^{+0.12}_{-0.11} \; ^{+0.15}_{-0.11}$	0.17	0.216 ± 0.023
$K_{\mu 2}$	$1.15 \; ^{+0.25}_{-0.21} \; ^{+0.16}_{-0.12}$	0.67	0.044 ± 0.005
$K_{\mu m}$	$1.06 \; ^{+0.35}_{-0.29} \; ^{+0.93}_{-0.34}$	0.40	0.024 ± 0.010

the prediction and expectation (Table 2) and show no indication of correlation between the cuts. The total predicted background is 0.30 ± 0.03 events and is dominated by $K^+ \to \pi^+\pi^0$. This background rate for 1.8×10^{12} stopped K^+ was intentionally selected to be higher than the 0.15 ± 0.04 background events expected for the entire E787 exposure of 5.9×10^{12} stopped K^+.

E949 elected to allow a higher total background in order to increase the signal acceptance. The E787 experience provides E949 with confidence in estimating the background rates and to more fully exploit the available data. By tightening the cuts, the background rate from each contributing processes can be reduced in a portion of the signal region. This knowledge, along with the acceptance in the same region, allows the signal region to be subdivided into 3781 cells with a predicted rate of background and signal acceptance in each cell. The $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction corresponding to an observation of candidates in such cells can then be evaluated using a likelihood ratio technique [5].

A single candidate was observed in the pre-determined signal region. Events passing all cuts except those on range and energy are shown in Figure 1. The observed candidate has all the characteristics of a $K^+ \to \pi^+\nu\bar{\nu}$ decay but its high values of P, R, and E as well as its low apparent pion decay time of 6.2 ns indicate a significant probability that it is due to $K^+ \to \mu^+ X$. The probability that the background alone could give rise to this event or any more signal-like event is 7% which is higher than the corresponding probabili-

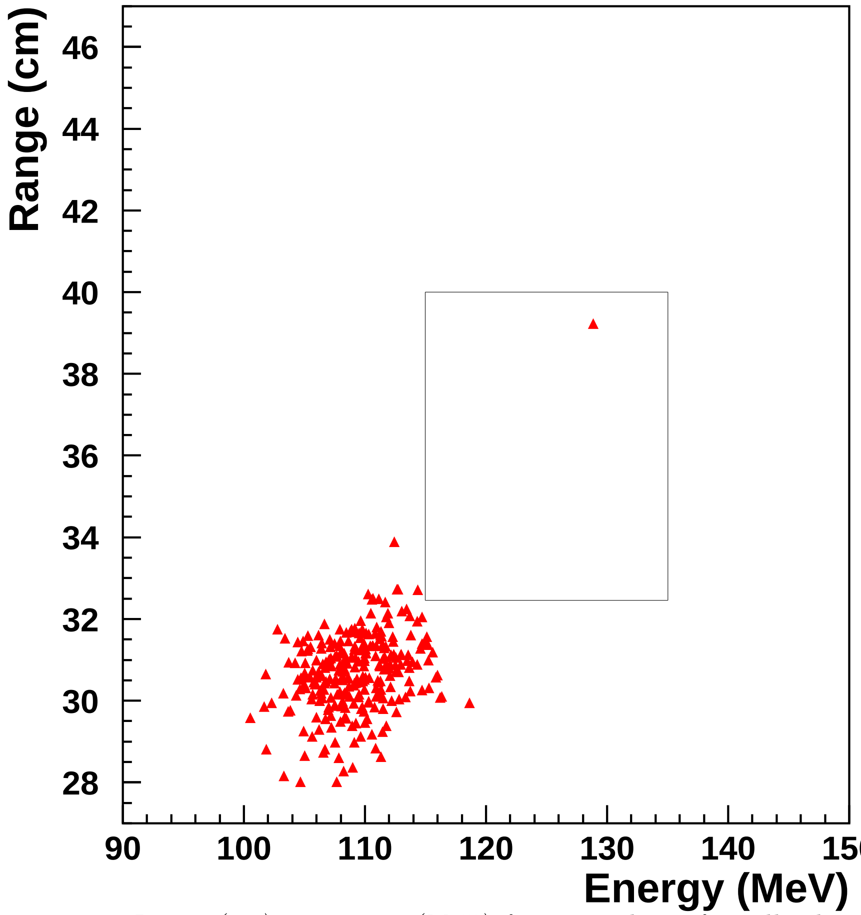

Figure 1: *Range (cm) vs Energy (MeV) for E949 data after all other cuts applied. The solid line shows signal region. The cluster of events near 110 MeV is unvetoed* $K^+ \to \pi^+\pi^0$.

ties of 0.7% and 2% of the candidates observed in E787. The probability that background alone could produce a more signal-like configuration than the three observed candidates is 0.1%. The $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction evaluated for all three candidates is $(1.47^{+1.30}_{-0.89}) \times 10^{-10}$ [6].

The upgrades to E787 resulted in improved photon veto rejection of $K^+ \to \pi^+\pi^0$ for the pnn1 region as well as the ability to accept higher instantaneous rates. The upgrades should permit comparable sensitivity in the kinematic region below the $K^+ \to \pi^+\pi^0$ peak ("pnn2"). Previous analyses of the pnn2 region by E787 have demonstrated that this region is dominated by background from $K^+ \to \pi^+\pi^0$ in which the kinematics of the charged pion are degraded by nuclear scattering in the target. The photon veto detector in the beam region is particularly important for suppression of this background process. Work is currently in progress to assess the impact of the upgrades to the photon veto detectors in the beam region and improvements to the algorithms that aid in the detection of the scattered pion.

E949 has observed an additional candidate for $K^+ \to \pi^+ \nu\bar{\nu}$ decay in the kinematic region above $K^+ \to \pi^+\pi^0$. Combined with the E787 results, $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$. Analysis of the kinematic region below $K^+ \to \pi^+\pi^0$ is in progress. Additional sources of funding are being sought to complete the E949 experiment. Given the importance of this mode to the understanding of the SM picture of CP violation, various programs to measure the $K^+ \to \pi^+\nu\bar{\nu}$ branching fraction at KEK, FNAL and CERN are under consideration [7].

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