The last BNL measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ Branching Ratio

version 0

E949 collaboration

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Abstract

Abstract goes here.

What is missing:

- *Better justification of the rationale for tightening the KIN cut.*
- *Less repitition.*
- *Probability of observed events to be background only.*
- *Table summarizing candidates.*
- *Probably some other stuff.*

The rate of $K^+ \to \pi^+\nu\bar{\nu}$ decays is amongst a handful of hadronic processes that can be precisely predicted in the standard model (SM) owing to knowledge of the transition matrix element from similar processes and minimal long-distance effects [1]. In addition the predicted branching fraction $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ is $(0.80 \pm 0.11) \times 10^{-10}$ [2] thus this decay provides a sensitive probe of non-SM effects. Previous studies of this decay experiment E787 at Brookhaven National Laboratory and its successor E949 have measured $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ based on three candidates in the pion momentum region $211 < P < 229$ MeV/c (pnn1) above the $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$) peak [3] and set a consistent limit of $< 22 \times 10^{-10}$ at 90% C.L. based on one candidate in the momentum region $140 < P < 195$ MeV/c (pnn2) below the $K_{\pi 2}$ peak [5].

In this Letter we report the results of a search for $K^+ \to \pi^+\nu\bar{\nu}$ below the $K_{\pi 2}$ peak using 1.7×10^{12} stopped K^+ decays obtained with E949 as well as the final results on $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ from all E787 and E949 data.

The E949 apparatus and analysis of the data in the pnn1 region has been described elsewhere [4] thus we concentrate on the apparatus and analysis features relevant for pnn2. Identification of $K^+ \to \pi^+\nu\bar{\nu}$ decays relies on detection of an incoming kaon and outgoing pion with no other detector activity. A 710 MeV/c K^+ beam was produced by 21.5 GeV proton interactions on a platinum target and passed through two electomagnetostatic separators during transport to the E949 scintillating fiber target. Typically 1.6×10^6 K^+/s entered the E949 target during a 2.2 s spill with a K^+/π^+ ratio of ~ 3.

Incoming kaons were identified by a Cerenkov counter and two proportional wire chambers before being slowed by a XX cm thick BeO degrader and a xx cm thick copper/scintillator active degrader (AD), passing through a beam hodoscope before stopping in the target. The AD comprised 40 layers of plastic scintillator (2 mm thick) and copper disks (2.2 mm) divided into 12 azimuthal segments. Scintillation light from each segment was transported via wavelength shifting fibers to a photomultiplier tube (PMT) that was readout out by time-to-digital convertors (TDCs), gallium-arsenide charge-coupled devices (CCDs) sampling at 500 MHz and analog-to-digital convertors (ADCs). The AD was capable of providing measurements of the incoming beam particle and activity concident with K^+ decay in the target.

The target consists of 413 5mm square and 3.1 m long scintillating fibers packed into a 12 cm diameter cylinder. Smaller "edge" fibers (1, 2 and 3.5 mm) filled the gaps near the target edge. Each 5 mm fiber was connect to a PMT and readout by ADCs, TDCs and CCDs. The edge fibers were grouped onto 16 PMTs with similar readout. The target could thus provide measurements of the incoming kaon and outgoing pion as well as evidence of additional activity in the target coincident with the outgoing pion.

The momentum, trajectory and position of the outgoing putative π^+ were measured in a drift chamber [7]. The outgoing pion is slows to a stop in a range stack (RS) of 19 layers of plastic scintillator with 24 segments in azimuth. PMTs on each end of the scintillator are readout by ADCs, TDCs and 500-MHz sampling transient digitizers (TDs) and enable measuremtn of the pion range (R) and kinetic energy (E) as well as the $\pi^+ \to \mu^+ \to e^+$ decay sequence.

The barrel veto and barrel veto liner (BVL) were lead/scintillator electromagnetic calorimeters of 14.3 and 2.9 radiation lengths at normal incidence, respectively, that provided photon vetoing over 2/3 of 4π sr solid angle. Photon vetoing over the remaining $\sim 1/3$ of 4π was provided by upstream and downstream end caps of undoped CsI (13.5 r.l.), upstream and downstream collar counters (~ 9 r.l.), microcollar ($\sim$? r.l.), upstream photon veto (3.1 r.l.) and downstream photon veto (DPV, ? r.l.). The latter detectors all utilized lead/scintillator technology. The AD (6.3 r.l.) and target (~ 7.3 r.l.) also provided additional photon veto capability.

Data were acquired with a multilevel trigger that required an entering kaon coming to rest in the target followed by an outgoing particle leaving the target at least 1.5 ns later that was identified as a pion via the $\pi^+ \to \mu^+$ signature in the RS TD readout and accompanied by no other activity. Additional pre-scaled triggers were used to accumulate $\mathrm{K}^+ \to \mu^+\nu(\gamma)$ ($\mathrm{K}_{\mu 2(\gamma)}$) and $\mathrm{K}_{\pi 2}$ decays as well as beam pions scattering in the target for monitoring and calibration purposes.

This analysis exploited experience gained previously [4] [6] [5] as well as detector upgrades of the AD, BVL and DPV to increase signal acceptance whilst maintaining a comparable total background. In addition the improved knowledge of the background contributions allowed the signal region to be divided into 9 sub-regions ("cells") with relative acceptance-to-background levels differing by a factor of ~ 3 that could be exploited by a likelihood method [8] to determined $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu})$.

We employed a "blind" analysis technique in which the signal region was not examined until all signal candidate selection criteria ("cuts") were established, the estimate of all backgrounds were completed and acceptance of all cells determined. At least two uncorrelated cuts with significant rejection were created for most backgrounds. Inversion of one of the pair of cuts could then be used to select a background-enriched data sample containing N events. Inversion of the complementary cut selected a data sample on which the rejection $\mathcal{R}$ of the first cut could be measured. The background was estimated as $N/(\mathcal{R}-)$. We ensured unbiased background estimates by dividing the data into one-third and two-third samples selected uniformly from the entire data set. Selection criteria were determined with the one-third sample and background estimated from the two-third sample. In contrast to the analysis of the pnn1 region, some backgrounds do not have sufficiently distinct characteristics to permit isolation by cut inversion of a pure background sample and permit a measurement of $\mathcal{R}$ with the data. For these backgrounds, we resorted to simulated data.

The largest background was due to $K_{\pi 2}$ decays in which the π^+ inelastically scatters in the target, losing energy and obscuring the directional correlation with the photons from the π^0 decay which would otherwise be detected in the barrel. The two cuts that suppressed this background were identification of π^+ scattering and detection of the photons from π^0 decay. The latter photon veto (PV) ability was improved in E949 with respect to E787 primarily due to the AD and BVL. Pion scattering was identified by kinks in the pattern of target fibers attributed to the outgoing pion, tracks that did not point back to the fiber containing the K^+ decay, energy deposits inconsistent with an outgoing pion or energy deposited in fibers traversed by the kaon at the time of the outgoing pion. The "CCDPUL" cut identified the latter signature by performing a least-squares fit to the CCD samples to identify the pulses due to the kaon and pion. The uncertainty in the $K_{\pi 2}$ target-scatter background has comparable statistical and systematic contributions 1. the systematic uncertainty is determined by the range of PV rejection values for samples of $K_{\pi 2}$ scatter events selected by different scattering signatures in the target or in different kinematic regions. There was also a much smaller background from $K_{\pi 2}$ due to scattering in the RS that was identified by the pattern of RS counters and the energy deposited to the π^+ track as well as PV suppression.

Additional backgrounds included $\mathrm{K}^+ \to \pi^+\pi^0\gamma$ ($K_{\pi 2\gamma}$), $\mathrm{K}^+ \to \pi^+\pi^- e^+\nu$ (K_{e4}), $\mathrm{K}^+\mu^+\nu(\gamma)$ and $\mathrm{K}^+ \to \pi^0\mu^+\nu$ (muon), scattered beam pions (beam) and $\mathrm{K}^0_\mathrm{L} \to \pi^+\ell^-\bar{\nu}$ where $\ell^+ = e^+$ or μ^+ resulting from K^+ charge-exchange (CEX) reactions. Simulated data were used to estimate the rejetion $\mathcal{R}$ of the cuts that suppress K_{e4}, $K_{\pi 2\gamma}$ and CEX backgrounds. These backgrounds could not be distinguished from the larger $\mathrm{K}_{\pi 2}$-scatter background based solely on the π^+ track. The K_{e4} process forms a background when the π^- and e^+ interact in the target without leaving a detectable trace. Positron interactions are well-modelled in our EGS-based simulation [9] and we used the π^- ionization spectrum in scintillator measured previously in E787 [10] to model π^- absorption. We assessed the systematic uncertainty in the K_{e4} background by varying the threshold of cuts on the energy deposited both in the kaon fibers at pion time and in non-kaon and non-pion fibers.

Measurement of the K^+ charge-exchange reaction were used as input to simulation of CEX events [11]. The requirement on the delayed coincidence (DC) between the reconstructed kaon and pion candidates provides suppression of CEX background as the emitted π^+ was required to be within the fiducial region of the target. The systematic uncertainty was assessed with the same methodology as the K_{e4} background.

The rejection of the $K_{\pi 2\gamma}$ background of the kinematic cuts (KIN) was calculated using a combination of simulated $\mathrm{K}_{\pi 2}$ and $K_{\pi 2\gamma}$ events and $\mathrm{K}_{\pi 2}$ data events. The additional PV rejection due to the radiative photon was calculated from the photon angular distribution in simulated events and the rejection power of single photons as a function of angle and energy evaluated with $\mathrm{K}_{\pi 2}$ data [12].

The remaining muon and beam backgrounds were estimated entirely from data and were very small 1. As previous analyses [6] [5] had shown the muon background to be small, the TD-based requirements on $\pi^+ \to \mu^+ \to e^+$ identification were loosened to gain

Figure 1: Energy *vs* range plots.

acceptance.

The reliability of the background estimates was checked by loosening the PV and CCDPUL cuts to define three regions just outside the signal region. Two of the regions, PV_1 and $CCDPUL_1$, were immediately adjacent to the signal region whilst a third region PV_2 was defined by further loosening of the PV cuts. The number of expected and observed events and the probability of the observation are given in Table 2. The overall 14% probability indicated that the observations were consistent with expectation although the 5.1% probability for the regions nearest the signal region may have indicated that the background was over-estimated. Given the inability to cleanly isolate each background component by cut inversion, some contamination is possible and generally inflates the background estimates. Re-evaluating the probabilities at the lower limit of the systematic uncertainties gives 13.0% (39.0%) for the two (three) closest regions and demonstrates that the assigned systematic uncertainties are reasonable.

After completion of the background studies, the signal region was examined and three candidates were found. The relative acceptance-to-background the cells containing the candidates was the $5^{\rm th}$, $7^{\rm th}$ and $9^{\rm th}$ lowest of the 9 pre-defined cells. The energy *vs* range for the observed candidates is shown in Figure 1 along with the results of previous E787 [3] and E949 [5] analyses. From the observed events, $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$ was calculated using the likelihood method [8] taking into account the uncertainties in the background and acceptance measurements. When combined with the results of previous E787 [3] and E949 [5] analyses, $\mathcal{B}(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ or $< 3.35 \times 10^{-10}$ at 90% CL. This result is consistent with the SM prediction but with a central value over twice as large.

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Bkgd comp.	Est. Tech.	Cut and add'l rejection or acceptance loss KIN	TD	DC	PV	REC	Entire region	B
$K_{\pi 2}$ TG	d	1.63			2.75	$\surd$	$0.619 \pm 0.150^{+0.067}_{-0.100}$	$0.1021 \pm 0.0244^{+0.0}_{-0.0}$
$K_{\pi 2}$ RS	d	1.63			2.75	$\surd$	$0.0303 \pm 0.0054^{+0.0038}_{-0.0039}$	$0.0050 \pm 0.0009 \pm 0.00$
$K_{\pi 2\gamma}$	ds	1.20			$\surd$		$0.0757 \pm 0.0073^{+0.0062}_{-0.0056}$	$0.0170 \pm 0.0016^{+0.0}_{-0.0}$
K_{e4}	ds	2.70			$\surd$		$0.176 \pm 0.072^{+0.233}_{-0.124}$	$0.0252 \pm 0.0103^{+0}_{-0}$
CEX	ds			6.7	$\surd$		$0.013 \pm 0.013^{+0.010}_{-0.003}$	$0.0007 \pm 0.0007^{+0.0}_{-0.0}$
Muon	d		3.08			$\surd$	0.0114 ± 0.0114	0.0014 ± 0.00
Beam	d			1.0	$\surd$		0.00134 ± 0.00083	0.0004 ± 0.00
Total background							$0.9267 \pm 0.1675^{+0.3200}_{-0.2365}$	$0.152 \pm 0.027^{+0}_{-0}$
Acc.		0.812	0.812	0.911	0.522	NA		

Table 1: An overly detailed summary of the background. Summary of the estimation technique, applicable cuts, additional rejection or acceptance loss, contributions to the entire signal region and best cell for each background component. The estimation technique "Est. Tech." indicates if only data (d) or data and simulation (ds) were used. The middle columns indicate the additional rejection for each component from the tightening of the kinematic (KIN), TD, delayed coincidence (DC), photon veto (PV) and reconstruction (REC) cuts. A $\surd$ indicates that the cut was inverted to determined the background. The bottom row gives the relative acceptance loss associated with the each cut.

Region	$N_{\rm exp}$	$N_{\rm obs}$	$\mathcal{P}(\leq N_{\rm obs}; N_{\rm exp})$	Combined
CCD_1	$0.79 \pm 0.35^{+0.30}_{-0.37}$	0	0.452 (0.652)	NA
PV_1	$9.09 \pm 0.65^{1.38}_{-1.15}$	3	0.020 (0.044)	0.051 (0.130)
PV_2	$32.4 \pm 1.9^{12.2}_{-7.9}$	34	0.613 (0.973)	0.140 (0.390)

Table 2: Comparison of the expected $N_{\rm exp}$ and observed $N_{\rm obs}$ numbers of events in three regions CCD_1, PV_1 and PV_2 near the signal region. The central value of $N_{\rm exp}$ is given along with the statistical and systematic uncertainties. $\mathcal{P}(\leq N_{\rm obs}; N_{\rm exp})$ is the probability of observing $N_{\rm obs}$ events or fewer when $N_{\rm exp}$ events are expected. The rightmost column "Combined" gives the probability of the combined observation in that region and the region(s) of the preceding row(s). The numbers in parentheses are the probabilities reevaluated when $N_{\rm exp}$ is reduced by the systematic uncertainty.

References

[1] Theory reference.

[2] Theory ref that gives br prediction

[3] pnn1 PRL

[4] pnn1 PRD

[5] pnn2 PRD

[6] pnn2 PLB

[7] UTC ref

[8] Junk ref

[9] EGS ref

[10] pi- abs ref

[11] CEX

[12] SPI measurement