# Improved Measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ Branching Ratio

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An additional event near the upper kinematic limit for $K^+ \to \pi^+ \nu\bar{\nu}$ has been observed by experiment E949 at Brookhaven National Laboratory. Combining previously reported and new data, the branching ratio is $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ based on three events observed in the pion momentum region $211 < P < 229$ MeV/$c$. At the measured central value of the branching ratio, the additional event had a signal-to-background ratio of 0.9.

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In the standard model (SM), the decay $K^+ \to \pi^+ \nu\bar{\nu}$ is sensitive to the couplings of top quarks which dominate the internal processes involved in this flavor changing neutral current reaction. A reliable SM prediction for the branching ratio $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.80 \pm 0.11) \times 10^{-10}$ [1,2] can be made due to knowledge of the hadronic transition matrix element from similar processes and minimal complications from hadronic effects. $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ is a sensitive probe of new physics since, for example, the apparent couplings between top and down quarks may also be determined by measurements in the B meson system resulting in a possible discrepancy [3,4]. In earlier studies, two events consistent with the decay $K^+ \to \pi^+ \nu\bar{\nu}$ were reported giving $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$ by experiment E787 at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory [5]. In this Letter, the first results from experiment E949 [6] at the AGS are presented.

Measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ decay from kaons at rest involved observation of the $\pi^+$ in the momentum region $211 < P < 229$ MeV/$c$ in the absence of other coincident activity. Pions were identified by comparing momentum ($P$), range ($R$), and energy ($E$) measurements and by observation of the $\pi^+ \to \mu^+ \to e^+$ decay sequence. Primary background sources were pions from the two-body decay $K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$), muons from $K^+ \to \mu^+ \nu$ ($K_{\mu 2}$) and other $K^+$ decays, pions scattered from the beam, and $K^+$ charge exchange reactions followed by $K^0_L \to \pi^+ l^- \bar{\nu}_l$, where $l = e$ or $\mu$.

The new data were acquired in 2002 using beams, apparatus, and procedures similar to those of experiment E787 [5,7–10]. The number of kaons stopped in the scintillating fiber target was $N_K = 1.8 \times 10^{12}$. Measurements of charged decay products were made in a 1 T magnetic field using the target, a central drift chamber, and a cylindrical range stack (RS) of scintillator detectors.

Photons were detected in a $4\pi$ sr calorimeter consisting of a lead/scintillator sandwich barrel veto detector (upgraded for E949) surrounding the RS, end caps of undoped CsI crystals, and other detectors. The upgraded apparatus also included replacement of one third of the RS, and an improved trigger system [10]. Although the instantaneous detector rates were twice those in E787, detector upgrades and the use of improved pattern recognition software enabled comparable acceptance to be obtained.

Each background source was suppressed by two groups of complementary but independent selection criteria (cuts), and the desired level of background rejection was obtained by adjusting the severity of the cuts. For example, the cut pair for $K_{\pi 2}$ background involved kinematic measurements of the $\pi^+$ and photon detection in $\pi^0 \rightarrow \gamma\gamma$ decay. The photon detection criteria, for instance, could be varied by changing the energy threshold and timing coincidence interval (relative to the $\pi^+$ signal) of the photon detectors. The effectiveness of each cut at rejecting background was determined using data selected by inverting the criteria of the complementary cut. Unbiased estimates of the effectiveness of the cuts were obtained using a uniformly sampled $1/3$ portion of the data for cut development and the remaining $2/3$ portion for background measurement. Examination of the predetermined signal region was avoided throughout the procedure. The level of signal acceptance as a function of cut severity was determined using data and simulations. This procedure enabled estimates of the expected background and signal rates inside and outside the signal region at different levels of background rejection and signal acceptance.

As a check of the method, the observed background levels near but outside the signal region were compared to the predicted background rates when both cuts for each background type were applied. The results are summarized in Table I for the two-body backgrounds, $K_{\pi 2}$ and $K_{\mu 2}$, and the multibody background ($K_{\mu m}$) with contributions from $K^+ \rightarrow \mu^+ \nu \gamma$, $K^+ \rightarrow \mu^+ \pi^0 \nu$, and $K_{\pi 2}$ with $\pi^+ \rightarrow \mu^+ \nu$ decay in flight. Five cases were considered corresponding to increasing background levels outside the signal region. For example, for the $K_{\mu 2}$ component, the region nearest to (farthest from) the signal region was chosen to have 7 (400) times the background expected in the signal region. The five ratios of the observed to predicted backgrounds were fitted to a constant $c$ for each background type. The consistency of $c$ with unity and the acceptable probability of $\chi^2$ of each fit confirmed both the independence of the pairs of cuts and the reliability of the background estimates. The measured uncertainties in the constants $c$ were used to estimate the systematic uncertainties in the predicted background rates in the signal region.

To estimate $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$, the parameter space of observables in the signal region was subdivided into 3781 bins corresponding to different ranges of cut severity, and each observed event could be assigned to the bin corresponding to its measured quantities. Bin $i$ was characterized by the value of $S_i/b_i$, the relative probability of an event in the bin to originate from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ($S_i$) or background ($b_i$) [5]. The signal rate of a bin was $S_i \equiv \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) A_i N_K$, where $A_i$ was the acceptance of the $i$th bin. Each observed event could also be described by a weight $W \equiv S/(S + b)$ that represented its effective contribution to $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$. $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ was obtained by a likelihood ratio technique [11] that determined the confidence level (C.L.) of a given branching ratio based on the observed events. For the 2002 data set, the candidate selection requirements were similar to those used previously. The predetermined signal region was enlarged, resulting in 10% more acceptance but also allowing more background. Estimated background levels dominated by $K_{\pi 2}$ and $K_{\mu 2}$ are listed in Table I.

Examination of the signal region for the new data set yielded one event with $P = 227.3 \pm 2.7$ MeV$/c$, $R = 39.2 \pm 1.2$ cm (in equivalent cm of scintillator), and $E = 128.9 \pm 3.6$ MeV. The event (2002A) has all the characteristics of a signal event, although its high momentum and low apparent time of $\pi \rightarrow \mu$ decay (6.2 ns) indicate a higher probability than the two previously observed

TABLE I. The fitted constants $c$ of the ratios of the observed to the predicted numbers of background events and the probability of $\chi^2$ of the fits for the $K_{\pi 2}$, $K_{\mu 2}$, and $K_{\mu m}$ 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 $0.014 \pm 0.003$ events, resulting in a total number of background events expected in the signal region of $0.30 \pm 0.03$.

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

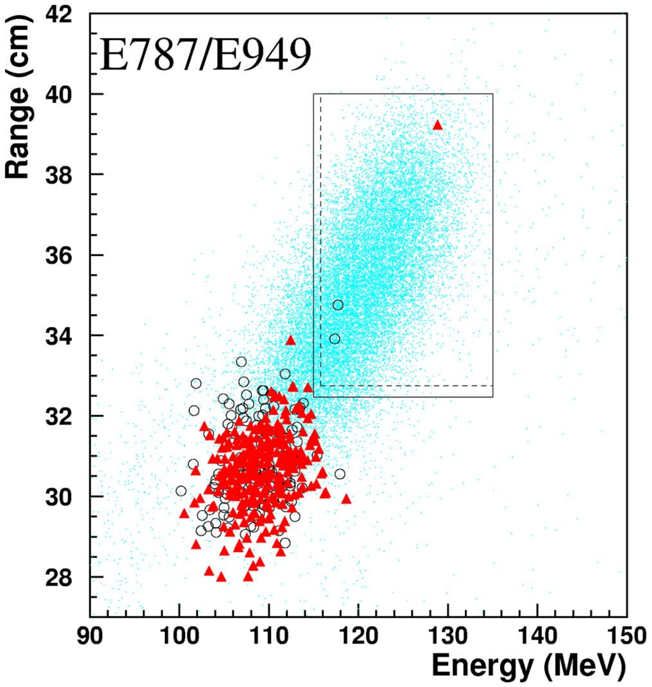

FIG. 1 (color online). Range versus energy distribution of events passing all other cuts of the final sample. The circles represent E787 data and the triangles represent E949 data. The group of events around $E = 108$ MeV was due to the $K_{\pi 2}$ background. The simulated distribution of events from $K^+ \to \pi^+ \nu \bar{\nu}$ decay is indicated by dots. The solid line (dashed line) box represents the signal region for E949 (E787).

candidate events that it was due to background, particularly $K_{\mu 2}$ decay.

The combined result for the E949 and E787 data is shown in Fig. 1, with the range and kinetic energy of the events surviving all other cuts. The result obtained from the likelihood method described above was $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$, incorporating the three observed events and their associated weights $W$ given in Table II. For event 2002A, the weight was $W = 0.48$ ($S/b = 0.9$). The estimated probability that the background alone gave rise to this or any more signal-like event was 0.07. Table II also shows the estimated probability that the background alone gave rise to each event (or any more signal-like event), the acceptances [5], $N_K$, and the total expected background levels. This result is consistent with the SM expectation [1,2]. The quoted 68% C.L. interval includes statistical and estimated systematic uncertainties. The 80% and 90% C.L. intervals for $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ were $(0.42, 3.22) \times 10^{-10}$ and $(0.27, 3.84) \times 10^{-10}$, respectively [13]. The estimated systematic uncertainties do not significantly affect the confidence levels. The estimated probability that background alone gave rise to the three observed events (or to any more signal-like configuration) was 0.001 [14].

The E787 and E949 data were also used to set a limit on the branching ratio for $K^+ \to \pi^+ X^0$, where $X^0$ is a neutral weakly interacting massless particle [15]. Previous E787 data produced a limit of $\mathcal{B}(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$ [5]. The new result was $\mathcal{B}(K^+ \to \pi^+ X^0) < 0.73 \times 10^{-10}$ (90% C.L.), based on the inclusion of event 2002A, which was observed within 2 standard deviations of the expected pion momentum.

TABLE II. Numbers of kaons stopped in the target $N_K$, total acceptance, total numbers of estimated background events for the E949 and E787 data samples [12], $S/b$ and $W$ for each observed candidate event calculated from the likelihood analysis described in the text, and the estimated probability that the background alone gave rise to each event (or any more signal-like event).

| | E787 | | E949 |
|---|---|---|---|
| $N_K$ | $5.9 \times 10^{12}$ | | $1.8 \times 10^{12}$ |
| Total Acceptance | $0.0020 \pm 0.0002$ | | $0.0022 \pm 0.0002$ |
| Total Background | $0.14 \pm 0.05$ | | $0.30 \pm 0.03$ |
| Candidate | 1995A | 1998C | 2002A |
| $S/b$ | 50 | 7 | 0.9 |
| $W$ | 0.98 | 0.88 | 0.48 |
| Background Probability | 0.006 | 0.02 | 0.07 |

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