Further Evidence for the Decay $K^+ \to \pi^+ \nu \bar{\nu}$

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Additional evidence for the rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ has been found in a new data set with comparable sensitivity to the previously reported result. One new event was observed in the pion momentum region examined, $211 < P < 229$ MeV/c, bringing the total for the combined data set to two. Including all data taken, the backgrounds were estimated to contribute 0.15 ± 0.05 events. The branching ratio is $B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$.

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The decay $K^+ \to \pi^+ \nu \bar{\nu}$ is very sensitive to the coupling of top to down quarks, V_{td}, in the Cabibbo-Kobayashi-Maskawa quark mixing matrix. In the context of the standard model (SM), the predicted branching ratio is $B(K^+ \to \pi^+ \nu \bar{\nu}) = 0.75 \pm 0.29 \times 10^{-10}$ [1]. In an earlier study, a single event consistent with the decay $K^+ \to \pi^+ \nu \bar{\nu}$ at a branching ratio of $B(K^+ \to \pi^+ \nu \bar{\nu}) = 1.5^{+3.5}_{-1.2} \times 10^{-10}$ was found [2,3]. In this Letter, final results from Experiment E787 [4,5] at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory are presented, including a new data sample of comparable sensitivity to that reported previously.

The observable signature for $K^+ \to \pi^+ \nu \bar{\nu}$ decay from kaons at rest involves only the π^+ track and π^+ decay products. Major background sources include the two-body decays $K^+ \to \mu^+ \nu_\mu$ ($K_{\mu 2}$) and $K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$), pions scattered from the beam, and K^+ charge exchange (CEX) reactions resulting in decays $K_L^0 \to \pi^+ l^- \bar{\nu}_l$, where $l = e$ or μ. In order to make an unambiguous measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$, it is advantageous to suppress all backgrounds well below the signal level.

The data discussed here were acquired during the 1998 run of the AGS, using kaons of 710 MeV/c incident on the apparatus at a rate of about 4 MHz. The kaons were detected and identified by Čerenkov, tracking, and energy-loss counters after which 27% reached a scintillating-fiber target used for kaon and pion tracking. Measurements of the momentum (P), range (R), and kinetic energy (E) of charged decay products were made using the target, a central drift chamber, and a cylindrical range stack (RS) made up of 21 layers of plastic scintillator with two layers of tracking chambers embedded in it, all within a 1-T solenoidal magnetic field. The $\pi^+ \to \mu^+ \to e^+$ decay sequence from pions which came to rest in the RS was observed using 500-MHz transient digitizers. Photons were detected in a calorimeter mainly consisting of a 14-radiation-length-thick barrel detector made of a lead/scintillator sandwich and 13.5-radiation-length-thick end caps of undoped CsI crystals.

To be accepted as a $K^+ \to \pi^+ \nu \bar{\nu}$ candidate, a decay particle must be positively identified as a π^+ by comparing P, R, and E measurements, and by observation of the $\pi^+ \to \mu^+ \to e^+$ decay sequence. Events containing other decay products including photons or beam particles were eliminated by detectors covering 4π sr. A clean hit pattern in the scintillating-fiber target and a delayed decay at least 2 ns after an identified K^+ suppressed background events due to CEX and scattered beam pions. The search was restricted to the measured momentum region $211 < P < 229$ MeV/c between the $K_{\mu 2}$ and $K_{\pi 2}$ peaks. The maximum pion momentum from $K^+ \to \pi^+ \nu \bar{\nu}$ decays at rest is 227 MeV/c.

The data analysis, described in Refs. [2,6], focused on obtaining detailed estimates of all backgrounds prior to examining the predetermined signal region. In order to evaluate observed events, the parameter space of observables for the 1998 data set was subdivided into 7500 bins with differing levels of expected backgrounds. The signal region was defined to include the first 486 bins and was not examined until the final step in the analysis procedure. The background expected in the signal region was estimated from $BG = \Sigma_{i=1}^{486} b_i$, where b_i is the expected number of background events from all sources in bin i. Assuming the SM value for the branching ratio, 7.5×10^{-11} [7], an expected signal number S_i was also obtained for each bin as $S_i = 7.5 \times 10^{-11} A_i N_K$, where A_i is the acceptance in bin i and N_K is the number of kaons. A signal-to-background function $f = \frac{S_i}{b_i}$ was defined to characterize each bin in terms of the relative probability of events occurring there to originate in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay or background. For the event observed in the 1995–1997 data set (event A) which passed the tightest cuts designed to evaluate candidate events, a similar procedure resulted in the signal-to-background function value $f^A = 35$, which indicated a very high probability that it was due to signal and a low level of consistency with any of the known sources of background.

For the 1998 data set, the final candidate selection requirements were similar to those used previously, although more stringent track reconstruction criteria were imposed. For the background sources listed above, the numbers of events expected were $n_{K_{\mu 2}} = 0.034^{+0.043}_{-0.024}$, $n_{K_{\pi 2}} = 0.012^{+0.003}_{-0.004}$, $n_{\text{beam}} = 0.004 \pm 0.001$ and $n_{\text{CEX}} = 0.016^{+0.005}_{-0.004}$, where the combined statistical and systematic uncertainties are given. In total, the background level anticipated in the signal region was $BG = 0.066^{+0.044}_{-0.025}$ events. For this level of background, the acceptance for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ was $A = \Sigma_{i=1}^{486} A_i = 0.00196 \pm 0.00005(\text{stat}) \pm 0.00010(\text{syst})$, obtained from the factors given in the last column of Table I. The estimated systematic uncertainty in the acceptance was due mostly to the uncertainty in pion-nucleus interactions.

TABLE I. Acceptance factors used in the measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ for the 1995–1997 and 1998 data sets. The "K^+ stop efficiency" is the fraction of kaons entering the target that stopped, and "π^+ stop efficiency" is the fraction of pions which stopped in the range stack without nuclear interactions or decay in flight. "Other kinematic constraints" include particle identification cuts.

Acceptance factors	1995–1997	1998
K^+ stop efficiency	0.704	0.702
K^+ decay after 2 ns	0.850	0.851
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ phase space	0.155	0.136
Solid angle acceptance	0.407	0.409
π^+ stop efficiency	0.513	0.527
Reconstruction efficiency	0.959	0.969
Other kinematic constraints	0.665	0.554
$\pi - \mu - e$ decay acceptance	0.306	0.392
Beam and target analysis	0.699	0.706
Accidental loss	0.785	0.751
Total acceptance	0.0021	0.00196

To confirm the background estimates, the selection criteria were relaxed [3,6] to allow about 14 times higher background, and all bins except those in the final signal region were examined. Two events were observed, in agreement with the number of expected background events $\Sigma_{i=487}^{7500} b_i = 0.9 \pm 0.7$ for this region. One of these (event B1) had a low value of the signal-to-background function $f^{\text{B1}} = 0.07$. The second event (event B2) had all the characteristics of a signal event, but a low apparent time of $\pi \rightarrow \mu$ decay resulted in an intermediate value for the signal-to-background function $f^{\text{B2}} = 0.7$ reflecting the possibility that it was due to $K_{\mu 2}$ decay [8].

Following the background study, the signal region for the 1998 data set was examined yielding one candidate event (event C) with $f^{\text{C}} = 3.6$. The kinematic values are $P = 213.8 \pm 2.7$ MeV/c, $R = 33.9 \pm 1.2$ cm (in equivalent cm of scintillator), and $E = 117.1 \pm 3.6$ MeV. A display of this event is shown in Fig. 1. Close inspection of event C indicates that it is consistent with being due to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay. Although a small amount (0.6 MeV in total) of coincident nontrack related energy was observed in the target, this level of additional energy was expected to occur randomly somewhere in the detector in about 11% of all events, and was well below the cut at 3 MeV on this parameter.

The combined result for E787 data taken between 1995 and 1998 is shown in Fig. 2, the range vs kinetic energy of

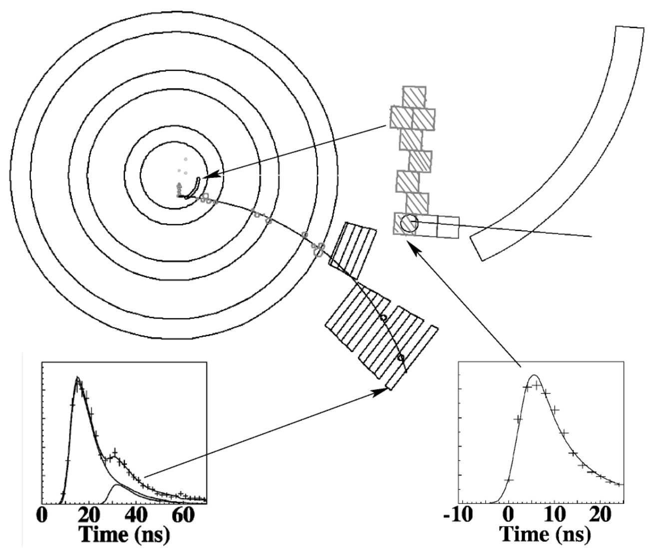

FIG. 1. Display of candidate event C. On the top left is the end view of the detector showing the track in the target, the drift chamber, and the range stack. On the top right is a blowup of the track in the target, where the hatched squares represent target fibers hit by the K^+ and the open squares indicate those hit by the π^+; a trigger scintillator that was hit is also shown. The lower right-hand box shows the digitized signal in the target fiber where the kaon stopped, indicating no additional activity. The pulse was sampled every 2 ns (crosses) and the solid line is a fit. The lower left-hand box shows the digitized $\pi \rightarrow \mu$ decay signal in the scintillator where the pion stopped. The curves are fits for the first, second, and combined pulses.

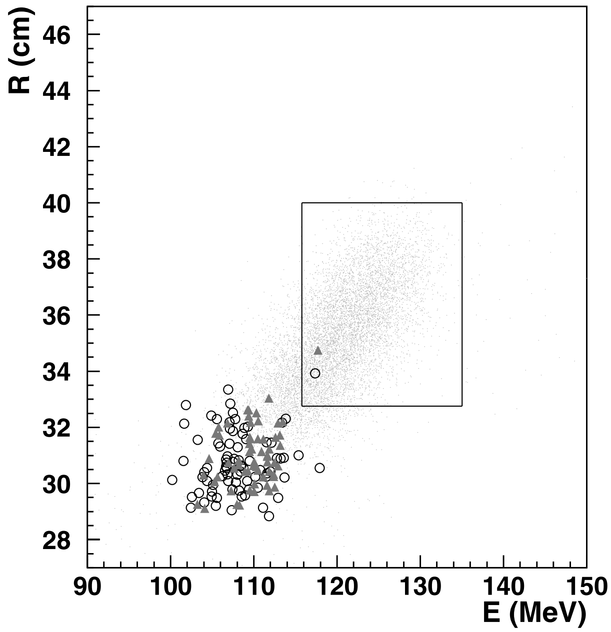

FIG. 2. Range vs energy plot of the final sample. The circles are for the 1998 data and the triangles are for the 1995–1997 data set. The group of events around $E = 108$ MeV is due to the $K_{\pi 2}$ background. The simulated distribution of expected events from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is indicated by dots.

events surviving all other cuts. In Fig. 2 the box represents the signal region in which two events (events A and C) appear. Using the f values of the observed events, a likelihood ratio technique [9] was used to determine the best estimate of the branching ratio. Based on two observed events with their associated f values, the acceptances given in Table I, the numbers of K^+ incident on the target, and the expected background levels given in Table II, the result is $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$ [10,11]. This result would be consistent with being due entirely to background only at the level of 0.02% [9].

Bounds on $|V_{td}|$ may be obtained from $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ by maximizing the charm quark contribution within the limits given in Ref. [1] and by assuming its phase relative to the top quark contribution to be 0° or 180°. The branching ratio limits given above along with $\bar{m}_t(m_t) = 166 \pm 5$ GeV/c^2, and $V_{cb} = 0.041 \pm 0.002$ [1], yield $0.007 < |V_{td}| < 0.030$ (68% C.L.) [12]. Note that these limits do not require knowledge of V_{ub} or ϵ_K. Alternatively, one can extract corresponding limits on the quantity $|\lambda_t|$ ($\lambda_t \equiv V_{ts}^* V_{td}$): $2.9 \times 10^{-4} < |\lambda_t| < 1.2 \times 10^{-3}$. In addition, the bounds $-0.88 \times 10^{-3} < \mathrm{Re}(\lambda_t) < 1.2 \times 10^{-3}$ can be obtained. For $\mathrm{Im}(\lambda_t)$, an upper limit of $\mathrm{Im}(\lambda_t) < 1.1 \times 10^{-3}$ (90% C.L.) is found. The bounds on λ_t are derived without reference to the B system or to measurements of ϵ_K or ϵ'/ϵ and are of particular interest because $\mathrm{Im}(\lambda_t)$ is proportional to the area of the unitarity triangle.

TABLE II. Numbers of kaons incident on the target, observed events, and total estimated background events expected for the 1995–1997 and 1998 data samples.

	1995–1997	1998
N_K	3.2×10^{12}	2.7×10^{12}
Observation (events)	1	1
Estimated background (events)	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

The limit found in the search for decays of the form $K^+ \rightarrow \pi^+ X^0$, where X^0 is a neutral weakly interacting massless particle [13], is $B(K^+ \rightarrow \pi^+ X^0) < 0.59 \times 10^{-10}$ (90% C.L.), based on zero events observed in a $\pm 2\sigma$ region around the pion kinematic end point.

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[7] The value assumed here is arbitrary and does not affect the result obtained for the branching ratio.
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[10] The uncertainties quoted indicate the 68% C.L. interval. The same analysis gave $B(K^+ \to \pi^+ \nu \bar{\nu}) > 0.56 \times 10^{-10}$ and $B(K^+ \to \pi^+ \nu \bar{\nu}) < 3.9 \times 10^{-10}$ at 90% C.L.
[11] The likelihood analysis when applied to the combined signal region and the enlarged background region, including events B1 and B2 discussed in the text, gave comparable results.
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