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

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An event consistent with the signature expected for the rare kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ has been observed. In the pion momentum region examined, $211 < P < 230$ MeV/c, the backgrounds are estimated to contribute 0.08 ± 0.03 events. If the event is due to $K^+ \to \pi^+ \nu \bar{\nu}$, the branching ratio is $4.2^{+9.7}_{-3.5} \times 10^{-10}$. [S0031-9007(97)04229-4]

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The decay $K^+ \to \pi^+ \nu \bar{\nu}$ has attracted interest due to its sensitivity to $|V_{td}|$, the coupling of top to down quarks in the Cabibbo-Kobayashi-Maskawa quark mixing matrix. Theoretical uncertainty in the branching ratio is minimal because the decay rate depends on short distance physics and because the hadronic matrix element can be extracted from the well-measured decay $K^+ \to \pi^0 e^+ \nu$. After next-to-leading-logarithmic analysis of QCD effects [1], calculation of isospin breaking, phase space differences, and other small corrections to the hadronic matrix element [2], and calculation of two-electroweak-loop effects [3], the intrinsic uncertainty is only about 7% [4]. Based on current knowledge of standard model (SM) parameters, the branching ratio $B(K^+ \to \pi^+ \nu \bar{\nu})$ is expected to be in the range $(0.6-1.5) \times 10^{-10}$ [5]. Long-distance contributions to the branching ratio (i.e., meson, photon exchange) appear to be negligible (10^{-13}) [6,7]. Since $K^+ \to \pi^+ \nu \bar{\nu}$ is a flavor changing neutral current process that is highly suppressed in the SM, it also serves as a hunting ground for non-SM physics. The signature $K^+ \to \pi^+$ "nothing" [6,8,9] includes $K^+ \to \pi^+ \nu \bar{\nu}$ with non-SM intermediate states (such as virtual supersymmetric particles), $K^+ \to \pi^+ \nu \bar{\nu}'$ (a lepton flavor violating final state), $K^+ \to \pi^+ X^0 X^{0'}$ where X^0 and $X^{0'}$ are not neutrinos, and $K^+ \to \pi^+ X^0$ where X^0 is a single, noninteracting particle. Initial results from the E787 experiment [10] at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory gave 90% confidence level (C.L.) upper limits $B(K^+ \to \pi^+ \nu \bar{\nu}) < 2.4 \times 10^{-9}$ and $B(K^+ \to \pi^+ X^0) < 5.2 \times 10^{-10}$ for a massless X^0 [11]. In this Letter, we report on the analysis of a new data sample with 2.4 times greater sensitivity, taken in 1995 using an upgraded beam and detector.

The signature for $K^+ \to \pi^+ \nu \overline{\nu}$ is a K^+ decay to a π^+ of momentum $P < 227$ MeV/c and no other observable product. Definitive observation of this signal requires suppression of all backgrounds to well below the sensitivity for the signal and reliable estimates of the residual background levels. Major background sources include the copious two-body decays $K^+ \to \mu^+ \nu_\mu$ ($K_{\mu 2}$) with a 64% branching ratio and $P = 236$ MeV/c and $K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$) with a 21% branching ratio and $P = 205$ MeV/c. The only other important background sources are scattering of pions in the beam and K^+ charge exchange (CEX) reactions resulting in decays $K_L^0 \to \pi^+ l^- \overline{\nu}$, where $l = e$ or μ. To suppress the backgrounds, techniques were employed that incorporated redundant kinematic and particle identification measurements and efficient elimination of events with additional particles.

Kaons of 790 MeV/c were delivered to the experiment at a rate of 7×10^6 per 1.6-s spill of the AGS. The kaon beam line (LESB3) incorporated two stages of particle separation resulting in a pion contamination of about 25%. The kaons were detected and identified by Čerenkov, tracking, and energy loss (dE/dx) counters. About 20% of the kaons passed through a degrader to reach a stopping target of 5-mm-square plastic scintillating fibers read out by 500-MHz CCD transient digitizers [12]. Measurements of the momentum (P), range (R, in equivalent cm of scintillator), and kinetic

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energy (E) of charged decay products were made using the target, a central drift chamber [13], and a cylindrical range stack with 21 layers of plastic scintillator and two layers of straw tube tracking chambers. Pions were distinguished from muons by kinematics and by observing the $\pi \rightarrow \mu \rightarrow e$ decay sequence in the range stack using 500-MHz flash-ADC transient digitizers (TD) [14]. Photons were detected in a 4π-sr calorimeter consisting of a 14-radiation-length-thick barrel detector made of lead/scintillator and 13.5 radiation lengths of undoped CsI crystal detectors (also read out using CCD digitizers) covering each end [15]. In addition, photon detectors were installed in the extreme forward and backward regions, including a Pb glass Čerenkov detector just upstream of the target. A 1-T solenoidal magnetic field was imposed on the detector for the momentum measurements.

In the search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, we required an identified K^+ to stop in the target followed, after a delay of at least 2 ns, by a single charged-particle track that was unaccompanied by any other decay product or beam particle. This particle must have been identified as a π^+ with P, R, and E between the $K_{\pi 2}$ and $K_{\mu 2}$ peaks. A multilevel trigger selected events with these characteristics for recording, and off-line analysis further refined the suppression of backgrounds. To elude rejection, $K_{\mu 2}$ and $K_{\pi 2}$ events would have to have been reconstructed incorrectly in P, R, and E. In addition, any event with a muon would have to have had its track misidentified as a pion—the most effective weapon here was the measurement of the $\pi \rightarrow \mu \rightarrow e$ decay sequence which provided a suppression factor 10^{-5}. Events with photons, such as $K_{\pi 2}$ decays, were efficiently eliminated by exploiting the full calorimeter coverage. The inefficiency for detecting events with π^0s was 10^{-6} for a photon energy threshold of about 1 MeV. A scattered beam pion could have survived the analysis only by misidentification as a K^+ and if the track were mismeasured as delayed, or if the track were missed entirely by the beam counters after a valid K^+ stopped in the target. CEX background events could have survived only if the K_L^0 were produced at low enough energy to remain in the target for at least 2 ns, if there were no visible gap between the beam track and the observed π^+ track, and if the additional charged lepton went unobserved.

The data were analyzed with the goal of reducing the total expected background to significantly less than one event in the final sample. In developing the required rejection criteria (cuts), we took advantage of redundant independent constraints available on each source of background to establish two independent sets of cuts. One set of cuts was relaxed or inverted to enhance the background (by up to 3 orders of magnitude) so that the other group could be evaluated to determine its power for rejection. For example, $K_{\mu 2}$ (including $K^+ \rightarrow \mu^+ \nu_\mu \gamma$) was studied by separately measuring the rejections of the TD particle identification and kinematic cuts. The background from $K_{\pi 2}$ was evaluated by separately measuring the rejections of the photon detection system and kinematic cuts. The background from beam pion scattering was evaluated by separately measuring the rejections of the beam counter and timing cuts. Measurements of K^+ charge exchange in the target were performed, which, used as input to Monte Carlo studies, allowed the background to be determined. Small correlations in the separate groups of cuts were investigated for each background source and corrected for if they existed.

The background levels anticipated with the final analysis cuts were $b_{K_{\mu 2}} = 0.02 \pm 0.02$, $b_{K_{\pi 2}} = 0.03 \pm 0.02$, $b_{\text{beam}} = 0.02 \pm 0.01$, and $b_{\text{CEX}} = 0.01 \pm 0.01$. In total, $b = 0.08 \pm 0.03$ background events were expected in the signal region [16]. Further confidence in the background estimates and in the measurements of the background distributions near the signal region was provided by extending the method described above to estimate the number of events expected to appear when the cuts were relaxed in predetermined ways so as to allow orders of magnitude higher levels of all background types.

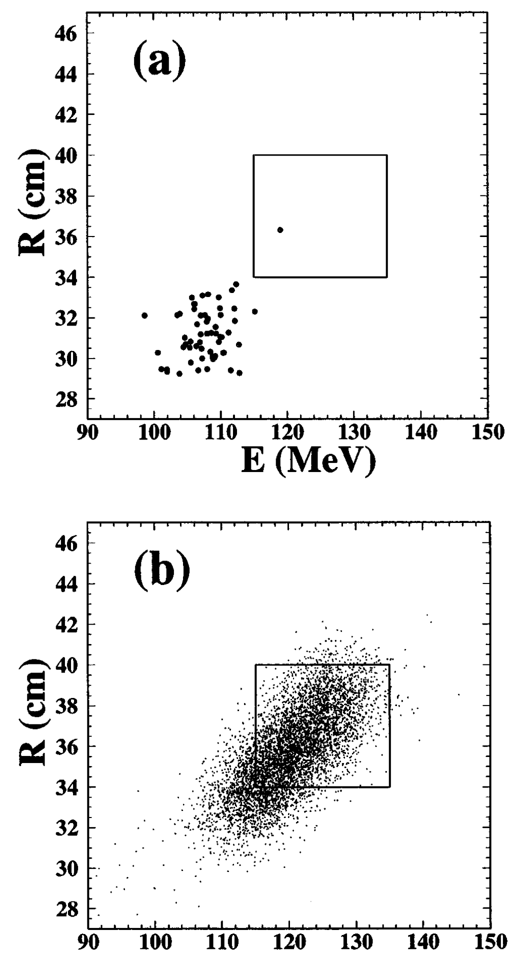

FIG. 1. (a) Range R vs energy E distribution for the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data set with the final cuts applied. The box enclosing the signal region contains a single candidate event. (b) The Monte Carlo simulation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with the same cuts applied.

Confronting these estimates with measurements from the full $K^+ \to \pi^+ \nu \bar{\nu}$ data, where the two sets of cuts for each background type were relaxed simultaneously, tested the independence of the two sets of cuts. At approximately the $20 \times b$ level we observed 2 events where 1.6 ± 0.6 were expected, and at the level $150 \times b$ we found 15 events where 12 ± 5 were expected. Under detailed examination, the events admitted by the relaxed cuts were consistent with being due to the known background sources. Within the final signal region, we still had additional background rejection capability. Therefore, prior to looking in the signal region, we established several sets of ever-tighter criteria which were designed to be used only to interpret any events that fell into the signal region.

Figure 1(a) shows R vs E for the events surviving all other analysis cuts. Only events with measured momentum in the accepted region $211 \leq P \leq 230$ MeV/c are plotted. The rectangular box indicates the signal region specified as range $34 \leq R \leq 40$ cm of scintillator (corresponding to $214 \leq P_\pi \leq 231$ MeV/c) and energy $115 \leq E \leq 135$ MeV ($213 \leq P_\pi \leq 236$ MeV/c) which encloses the upper 16.2% of the $K^+ \to \pi^+ \nu \bar{\nu}$ phase space. One event was observed in the signal region. The residual events below the signal region clustered at $E = 108$ MeV were due to $K_{\pi 2}$ decays where both photons had been missed. The number of these events is consistent with estimates of the photon detection inefficiency.

A reconstruction of the candidate event is shown in Fig. 2, and the momentum and timing of the candidate event are shown in relation to enhanced background distributions in Fig. 3. Measured parameters of the event include $P = 219.1 \pm 2.9$ MeV/c, $E = 118.9 \pm 3.9$ MeV, $R = 36.3 \pm 1.4$ cm, and decay times $K \to \pi$, $\pi \to \mu$, and $\mu \to e$ of 23.9 ± 0.5 ns, 27.0 ± 0.5 ns, and 3201.1 ± 0.7 ns, respectively. No significant energy was observed elsewhere in the detector in coincidence with the pion [17]. The event also satisfied the most demanding criteria designed in advance for candidate evaluation. This put it in a region with an additional background rejection factor of 10. In this region, $b' = 0.008 \pm 0.005$ events would be expected from known background sources while 55% of the final acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$ would be retained [18]. Since the explanation of the observed event as background is highly improbable, we conclude that we have likely observed a kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$.

To calculate the branching ratio indicated by this observation, we used the final acceptance for $K^+ \to \pi^+ \nu \bar{\nu}$, $A = 0.0016 \pm 0.0001(\text{stat}) \pm 0.0002(\text{syst})$ derived from the factors given in Table I, and the total exposure of

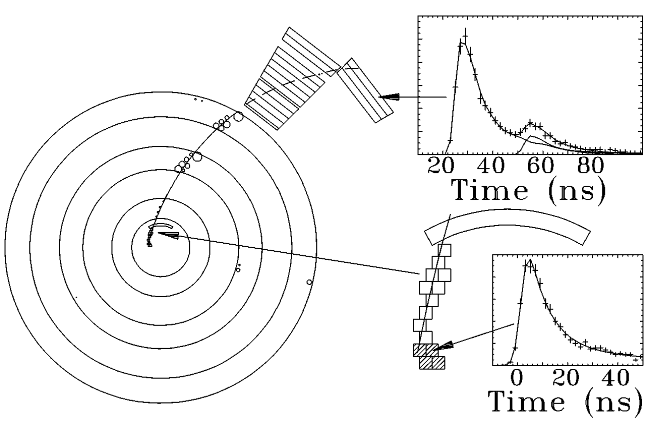

FIG. 2. Reconstruction of the candidate event. On the left is the end view of the detector showing the track in the target, drift chamber (indicated by drift-time circles), and range stack (indicated by the layers that were hit). At the lower right is a blowup of the target region where the hatched boxes are kaon hits, the open boxes are pion hits, and the inner trigger counter hit is also shown. The pulse data sampled every 2 ns (crosses), in one of the target fibers hit by the stopped kaon, is displayed along with a fit (curve) to the expected pulse shape. At the upper right of the figure is the $\pi \to \mu$ decay signal in the range stack scintillator layer where the pion stopped. The crosses are the pulse data sampled every 2 ns, and the curves are fits for the first, second, and combined pulses.

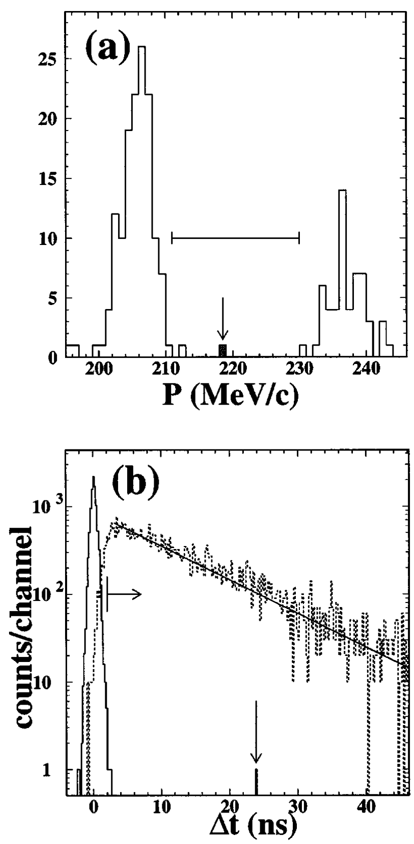

FIG. 3. Enhanced background distributions. (a) The histogram shows the momentum spectrum with backgrounds enhanced by an order of magnitude by loosening the range, photon, and TD particle identification cuts. The peaks are due to $K_{\pi 2}$ and $K_{\mu 2}$. The candidate event (vertical arrow) is shown in relation to the accepted region (horizontal bar). (b) The time difference Δt between the π^+ and the K^+ signals in the stopping target for the candidate event (vertical arrow) and for a sample of events identified as scattered beam pions (solid histogram). Also shown is the delay timing cut position (horizontal arrow) and the measured time distribution for kaon decays (dotted histogram). The straight line shows the K^+ lifetime.

TABLE I. Acceptance factors used in the measurement of $K^+ \to \pi^+ \nu \bar{\nu}$. The "$K^+$ stop efficiency" is the fraction of kaons entering the target that stopped, and "other kinematic constraints" includes kinematic particle identification and dE/dx cuts.

Acceptance factors	
K^+ stop efficiency	0.75
K^+ decay after 2 ns	0.813
$K^+ \to \pi^+ \nu \bar{\nu}$ phase space	0.162
Solid angle acceptance	0.386
π^+ nucl. int., decay-in-flight	0.502
Reconstruction efficiency	0.956
Other kinematic constraints	0.713
$\pi - \mu - e$ decay acceptance	0.247
Beam and target analysis	0.659
Accidental loss	0.747
Total acceptance	0.0016

$N_{K^+} = 1.49 \times 10^{12}$ kaons entering the target. Where possible, we employed calibration data taken simultaneously with the physics data for the acceptance calculation. We relied on Monte Carlo studies only for the solid angle acceptance factor, the π^+ phase space factor, and the losses from π^+ nuclear interactions and decays in flight. Figure 1(b) shows the simulated R vs E distribution for $K^+ \to \pi^+ \nu \bar{\nu}$ with final analysis cuts applied. The systematic uncertainty in the acceptance was estimated to be about 10%. This was confirmed by comparing a parallel measurement of the $K_{\pi 2}$ branching ratio to the world-average value. If the observed event is due to $K^+ \to \pi^+ \nu \bar{\nu}$, the branching ratio is $B(K^+ \to \pi^+ \nu \overline{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$.

The likelihood of the candidate event being due to $K^+ \to \pi^+ X^0$ ($M_{X^0} = 0$) is small. Based on the measured resolutions, the χ^2 C.L. for consistency with this hypothesis is 0.8%. Thus, using the acceptance for $K^+ \to \pi^+ X^0$, $A_{(K^+ \to \pi^+ X^0)} = 0.0052 \pm 0.0003(\text{stat}) \pm 0.0007(\text{syst})$, and no observed events in the region $221 < P < 230$ MeV/c, a 90% C.L. upper limit of $B(K^+ \to \pi^+ X^0) < 3.0 \times 10^{-10}$ was derived.

The observation of an event with the signature of $K^+ \to \pi^+ \nu \bar{\nu}$ is consistent with the expectations of the SM which are centered at about 1×10^{-10}. Using the result for $B(K^+ \to \pi^+ \nu \bar{\nu})$ and the relations given in Ref. [1], $|V_{td}|$ lies in the range $0.006 < |V_{td}| < 0.06$ [19]. E787 has recently collected additional data and the experiment is continuing.

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[16] An order of magnitude improvement in background suppression was obtained relative to Ref. [11]. The $K_{\mu 2}$ ($K_{\mu 2 \gamma}$) and $K_{\pi 2}$ backgrounds were reduced due to a factor of 2 better momentum resolution (see [13]) and to improved photon detectors (see [15]). The beam and CEX backgrounds were reduced, in part, due to improved timing resolutions (see [12]).
[17] There are a few scattered hits off the track in the drift chamber which are consistent with being due to random noise.
[18] The background estimates in the region with the tightest cuts were $b_{K_{\mu 2}} = 0.004 \pm 0.004$, $b_{K_{\pi 2}} = 0.001 \pm 0.001$, $b_{\text{beam}} = 0.002 \pm 0.002$, and $b_{\text{CEX}} = 0.002 \pm 0.002$.
[19] These limits include the values of $|V_{td}|$ consistent with the unitarity of the quark mixing matrix, the range of $B(K^+ \to \pi^+ \nu \overline{\nu})$ given in the text, and the ranges of V_{cb}, m_c, m_t, and $\Lambda_{\overline{MS}}$ given in Ref. [4]. However, they are independent of (and consistent with) information on $|V_{ub}/V_{cb}|$, $B - \overline{B}$ mixing, or CP violation in the K system used in other estimates of the range of $|V_{td}|$.