Further search for the decay $K^+ \to \pi^+ \nu\bar{\nu}$ in the momentum region $P < 195$ MeV/c

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We report the results of a search for the decay $K^+ \to \pi^+ \nu\bar{\nu}$ in the kinematic region with $\pi^+$ momentum $140 < P < 195$ MeV/c using the data collected by the E787 experiment at BNL. No events were observed. When combined with our previous search in this region, one candidate event with an expected background of 1.22 ± 0.24 events results in a 90% C.L. upper limit of $2 \times 10^{-9}$ on the branching ratio of $K^+ \to \pi^+ \nu\bar{\nu}$. We also report improved limits on the rates of $K^+ \to \pi^+ X^0$ and $K^+ \to \pi^+ X^1 X^2$ where $X^0, X^1, X^2$ are hypothetical, massless, long-lived neutral particles.

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The decay $K^+ \to \pi^+ \nu\bar{\nu}$ is a flavor changing neutral current process which is highly suppressed at tree level by the Glashow-Iliopoulos-Maiani mechanism; however, the breaking of flavor symmetry, which results in differences in the quark masses, allows this decay to proceed at a very small rate at the loop level. The large top quark mass results in dominance of the top quark contribution, making this decay very sensitive to the coupling of the top quark to the down quark, $V_{td}$, in the Cabibbo-Kobayashi-Maskawa mixing matrix. The branching ratio for this rare decay has been measured to be $(1.47^{+1.30}_{-1.09}) \times 10^{-10}$ based on the observation of three events in the $\pi^+$ momentum phase space region $P > 211$ MeV/c (Region 1), using the data collected by the E787 experiment at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory. The standard model (SM) predicts the branching ratio for this decay mode to be $(0.78 \pm 0.12) \times 10^{-10}$. Physics beyond the SM involving new heavy particles can interfere with the SM diagrams and alter the decay rate and the kinematic spectrum. It is therefore important to obtain higher statistics for this decay and to extend the measurement to other regions of phase space. In an earlier paper, we reported the results from the kinematic search region below the $K^+ \to \pi^+ \pi^0 (K_{12})$ peak with $\pi^+$ momentum, $140 < P < 195$ MeV/c (Region 2), using the data collected by the E787 experiment during the 1996 run. In this letter, we present results for the same kinematic region from additional data collected during the 1997 run.

Event recognition for $K^+ \to \pi^+ \nu\bar{\nu}$ must rely on the detection of the incoming kaon and the outgoing pion only, since the two neutrinos are undetectable. Kaons were produced by 24 GeV protons from the AGS impinging on a 6 cm long platinum target. The beam was then transported, purified, and momentum selected using electrostatic separators, two dipole magnets, sev-
Kaons. Čerenkov light from the lead-glass was collected from kaon decays, while being insensitive to the incident incoming pions as well as electromagnetic showers. A cylindrical lead-glass detector, which operated down by a passive BeO degrader and a lead-glass detector, was designed to de-activate a Čerenkov light radiator (11.2 cm diameter and 10 cm long or 3.5 radiation lengths) was planned to detect kaons and pions in the ratio of 4:1. The incoming beam particles were identified by a Čerenkov counter and wire chambers and were slowed down by a passive BeO degrader and a lead-glass detector. The cylindrical lead-glass detector, which operated as a Čerenkov light radiator (11.2 cm diameter and 10 cm long or 3.5 radiation lengths) was designed to detect incoming pions as well as electromagnetic showers from kaon decays, while being insensitive to the incident kaons. Čerenkov light from the lead-glass was collected from the sides of the cylinder by a 1 cm thick Lucite sleeve coupled with silicone gel. The Lucite sleeve was glued to 16 azimuthally segmented trapezoidal lead-glass pieces. Each of these pieces was instrumented with a fine-mesh photo-multiplier tube (PMT) which was operated in the 1 T magnetic field. The PMTs were located in a ring surrounding the BeO degrader and were read out by TDCs. Kaons were stopped in the target consisting of 413 mm × 5 mm × 3.1 mm long plastic scintillating fibers, packed axially to form a 12 cm diameter cylinder. Each fiber was read out by a PMT. Gaps in the outer edges of the target were filled with 3.5 mm, 2 mm, and 1 mm fibers which were connected to PMTs in groups. The PMTs were read out by ADCs, TDCs, and 500 MHz transient digitizers based on GaAs charge-coupled devices (CCDs). The location, trajectory and momentum of the outgoing charged particles were measured by a drift chamber. The range (R) and kinetic energy (E) of the charged particles were measured in a 21 layer Range Stack of plastic scintillator and the target. The signals from the PMTs mounted on the Range Stack were recorded by ADCs and by 500 MHz transient digitizers (TDs). The TDs had the ability to record pulses for 6.4 microseconds after the event trigger, which enabled the observation of the decay sequence, π⁺ → μ⁺ → e⁺ in the Range Stack. An electromagnetic calorimeter consisting of a 14-radiation length lead/scintillator barrel detector and 13.5-radiation length endcaps of undoped CsI crystals was used to veto photons. Also, two collar counters composed of lead/scintillator with a total thickness of 4.6 radiation lengths and a microcollar detector composed of plastic scintillator fibers and lead foil stacked around the beamline with a radial thickness of 0.7 radiation length were used to detect photons which traveled at small angles relative to the beamline and thereby missed the barrel detector and the endcap detector. Fig. 1 shows schematic side and end views of the E787 detector.

The data were obtained with a flux of 4.2 × 10⁶ kaons per 1.6 s long spill (period of 3.6 s) and with incident kaon momenta of 710 MeV/c or 670 MeV/c. A multilevel π⁺ν⁺ trigger ensured that a kaon entered the target and decayed at rest, with an outgoing particle identified as a pion by the π⁺ → μ⁺ decay sequence observed in the TD read-out of the Range Stack, and with no other accompanying particles such as photons. In addition to the π⁺ν⁺ trigger, several monitor triggers with variable pre-scale factors were used to accumulate events from K⁺ → μ⁺νμ (K_{μ2}) and K_{τ2} decays. A total of about 100 events per spill were written to data storage devices.

To eliminate possible selection bias, a “blind” analysis technique was used, which required the background sources to be identified a priori and the signal region to be pre-defined. The events in the signal region were not counted or examined until the cuts and the background estimates were final. At least two uncorrelated cuts with high rejection were designed for most of the backgrounds. Each of these cuts was independently reversed to create high statistics background samples to study the rejection power of the other cut. To minimize bias in the background measurements, the data were divided into one-third and two-third samples selected uniformly from the entire data set. Cuts were designed and optimized on the one-third sample and the background was then measured on the two-third sample.

As discussed in Ref. 15, the background in Region 2 was found to be dominated by K_{τ2} events in which the charged pion underwent a nuclear interaction near the kaon decay vertex, most probably on a carbon nucleus in the target plastic scintillator. The scattering of the pion reduced its kinetic energy into the signal region and removed the directional correlation with the photons from...
the π0 decay, most of which would otherwise be detected by the barrel detector. The limited efficiency of the photon detectors along the beam axis enhanced this background. During the 1997 run the lead-glass detector efficiency was improved in order to further suppress this background; however, most of the electromagnetic showers detected in the lead-glass detector were also observed in the endcap detector so that no additional background rejection was achieved. The improved efficiency of the lead-glass detector did, however, enable an increase in the photon veto efficiency by about 10% with respect to the 1996 data analysis.

The two sets of analysis tools for suppressing the scattered Kπ2 background were the detection of photons from the π0 decay and the identification of the π+ scattering in the target. The signatures for scattering included kinks in the pattern of target fibers attributed to the outgoing pion, tracks that did not point back to the fiber in which the kaon decayed, energy deposits inconsistent with the ionization energy loss for a pion of the measured momentum, extra deposited energy at the time of the outgoing pion in one of the target fibers traversed by the kaon. The extra energy left by pions in fibers traversed by the kaon was identified by examining the pulse shapes recorded in the CCDs for each kaon fiber using a χ2 fit. Events were rejected in which an overlapping second pulse, coincident in time with the pion, was found to have energy larger than 1.5 MeV [17]. Improved calibration of the target CCDs as well as this higher energy threshold for the second pulse energy resulted in about 7% more acceptance with the same level of background reduction in the 1997 data set as compared to the 1996 data set [15].

The other backgrounds in the search for K+ → π+ν̅ν in Region 2 were K+ → π+π0γ (Kππγ), K+ → π+μγ (Kπμγ), K+ → π+νeνe (Kπeν), scattered beam pions, and K+ charge exchange (CEX) reactions resulting in decays Kπ1− → π+→νν̅, where l = e or μ. The contribution from these processes to the total background was small compared to scattered Kπ2 decays. The techniques used to measure these backgrounds were discussed in [15]. Table I summarizes the contribution from each background process. The uncertainties include both statistical and systematic uncertainties.

| Process | Background |
|---------|------------|
| K+ → π+π0 | 0.40 ± 0.15 |
| K+ → π+π0γ | 0.006 ± 0.002 |
| Kπ2γ + Kπ3 | 0.009 ± 0.009 |
| Beam | 0.033 ± 0.030 |
| K+ → π+π−e+νe | 0.026 ± 0.026 |
| CEX | 0.013 ± 0.013 |
| Total | 0.49 ± 0.16 |

TABLE I: Expected number of background events in the search for K+ → π+ν̅ν in Region 2 for the 1997 data set. The total background in the analysis of the 1996 data set was measured to be 0.73 ± 0.18 in the same search region [15]. The errors include both statistical and systematic uncertainties.

The total background in the analysis of the 1996 data set was 0.69 ± 0.18 in the same search region [15]. The two sets of analysis tools for suppressing the scattered Kπ2 background were the detection of photons from the π0 decay and the identification of the π+ scattering in the target. The signatures for scattering included kinks in the pattern of target fibers attributed to the outgoing pion, tracks that did not point back to the fiber in which the kaon decayed, energy deposits inconsistent with the ionization energy loss for a pion of the measured momentum, extra deposited energy at the time of the outgoing pion in one of the target fibers traversed by the kaon. The extra energy left by pions in fibers traversed by the kaon was identified by examining the pulse shapes recorded in the CCDs for each kaon fiber using a χ2 fit. Events were rejected in which an overlapping second pulse, coincident in time with the pion, was found to have energy larger than 1.5 MeV [17]. Improved calibration of the target CCDs as well as this higher energy threshold for the second pulse energy resulted in about 7% more acceptance with the same level of background reduction in the 1997 data set as compared to the 1996 data set [15].

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| Process | Background |
|---------|------------|
| K+ stopping efficiency | 0.708 |
| Time consistency cuts | 0.672 |
| K+ → π+ν̅ν phase space | 0.345 |
| Geometry | 0.311 |
| π+ nucl. int. and decay in flight | 0.708 |
| Reconstruction efficiency | 0.943 |
| Kinematic cuts | 0.697 |
| π−μ−e decay chain | 0.490 |
| Beam and Target analysis | 0.494 |
| CCD acceptance | 0.431 |
| Photon veto efficiency | 0.390 |
| Total acceptance | 9.7 × 10−4 |
| Total number of stopped K+ | 0.61 × 10−2 |
| Single Event Sensitivity | 1.69 × 10−9 |

TABLE II: Acceptance factors used in the measurement of K+ → π+ν̅ν in Region 2. “Time consistency cut” requires consistent times of the charged particles measured in different detector elements. “Geometry” includes the trigger efficiency and the efficiency of the first two layers of the Range Stack. The uncertainty in the total acceptance is about 10% which includes both statistical and systematic uncertainties. Single event sensitivity is defined as the inverse of the product of the acceptance and the total number of stopped kaons.

FIG. 2: Kinetic energy (in MeV) versus range (in cm of plastic scintillator) distribution of events that remained after all cuts except that on momentum (top), and after the momentum cut (bottom). The triangles represent data from the 1996 run and the circles represent data from the 1997 run. Events from Monte Carlo simulation of K+ → π+ν̅ν are represented by the light dots. The group of events around 108 MeV was due to Kπ2 decays and the events at higher energy were due to Kπ3 decays. All events except for the one in the signal region (shown by the rectangular box) were eliminated by the 140 < P < 195 MeV/c cut on momentum.
tainty in the background estimate due to scattered $K_{\pi 2}$ events was dominated by the systematic uncertainty of the photon veto efficiency. This systematic uncertainty was estimated by measuring the photon veto efficiency on several sets of scattered $K_{\pi 2}$ events; each set was tagged by a different signature for the scattering in the target. The background estimates from the other processes were limited by statistics of the data samples. Table 1 shows the acceptance factors and single event sensitivity. We gained about 6% acceptance in the $K^+$ stopping efficiency due to the lower beam momentum during the 1997 run; another 14% gain in acceptance was achieved by better optimization of cuts on the relative times of signals from the beam and target detectors. However, we lost about 11% in acceptance in the detection of the $\pi^+ \rightarrow \mu^+$ decay sequence due to a fault in the $\pi^+\nu\bar{\nu}$ trigger during the 1997 run. The effective branching ratio of the background is measured to be $0.486 \times 1.69 \times 10^{-9} = 8.2 \times 10^{-10}$, which remains unchanged from the analysis of the 1996 data set [15]. The analysis and detector improvements described in this paper led to an acceptance increase of about 27% from the previous analysis [15].

Once the background estimates were finalized, the signal region (Region 2) was examined. No events were observed in the 1997 data set. The observation of one candidate event in the combined 1996-97 data set is consistent with the total background estimate of $1.22 \pm 0.24$. Fig. 2 shows the kinematics of the remaining events before and after the cut on momentum ($140 < P < 195$ MeV/c) for the combined data set. The event, reported in [15], has $P = 180.7$ MeV/c, $R = 22.1$ cm, and $E = 86.3$ MeV with a kaon decay time of 17.7 ns.

The total numbers of $K^+$ stopped in the target were $1.12 \times 10^{12}$ and $0.61 \times 10^{12}$ for the 1996 and 1997 data sets, respectively. Using the combined $K^+$ exposure, the acceptance of $7.65 \times 10^{-4}$ from the 1996 data set [15] and that reported in Table 1 and the observation of one event in Region 2, we calculated the upper limit of $B(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 2.2 \times 10^{-9}$ (90% C.L.) [15]. This result is a factor of two smaller than the result reported in [15].

For non-standard scalar and tensor interactions in the process of $K^+ \rightarrow \pi^+X^1X^2$, where $X^1$ and $X^2$ are hypothetical, massless, long-lived neutral particles, we set upper limits on their branching ratios at $2.7 \times 10^{-9}$ and $1.8 \times 10^{-9}$, respectively (90% C.L.) [15, 20].

This measurement is also sensitive to $K^+ \rightarrow \pi^+X^0$, where $X^0$ is a hypothetical long-lived weakly interacting particle, or system of particles. Fig. 3 shows the 90% C.L. upper limits on $B(K^+ \rightarrow \pi^+X^0)$ together with the previous limit from [15].

The search for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ in Region 2 was background limited and another factor of five in background reduction is needed to achieve a signal to noise ratio of one with the measured branching ratio in [2]. New data from experiment E949 [1], an upgraded version of E787, will provide further information in both $K^+ \rightarrow \pi^+\nu\bar{\nu}$ phase space regions.

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