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Search for the decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ X^0$ for $150 < M_{X^0} < 250 \text{ MeV}/c^2$

M. S. Atiya, I-H. Chiang, J. S. Frank, J. S. Haggerty, M. M. Ito,* T. F. Kycia,
K. K. Li, L. S. Littenberg, A. Sambamurti,† A. Stevens, and R. C. Strand
Brookhaven National Laboratory, Upton, New York 11973

W. C. Louis

Medium Energy Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

D. S. Akerib,‡ D. R. Marlow, P. D. Meyers, M. A. Selen,§ F. C. Shoemaker,
and A. J. S. Smith

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

E. W. Blackmore, D. A. Bryman, L. Felawka, P. Kitching, A. Konaka, Y. Kuno,||
J. A. Macdonald, T. Numao, P. Padley, J.-M. Poutissou, R. Poutissou, J. Roy,
R. Soluk, and A. S. Turcot

TRIUMF, Vancouver, British Columbia, Canada V6T 2A3

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A search for the decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ X^0$, where X^0 is any weakly interacting neutral particle or system of neutral particles with $150 < M_{X^0} < 250 \text{ MeV}/c^2$, was performed in the pion kinematic region below the $K_{\pi 2}$ ($K^+ \rightarrow \pi^+ \pi^0$) peak. An upper limit on $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ is set at 1.7×10^{-8} (90% C.L.) and $B(K^+ \rightarrow \pi^+ X^0)$ is restricted to the 10^{-7} level or lower. Limits are also set for the production of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ through scalar or tensor interactions at 1.8×10^{-8} and 1.0×10^{-8} (90% C.L.), respectively.

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The first-order forbidden flavor-changing neutral current process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is allowed at second order in the standard model of weak interactions due to the incomplete cancellation of diagrams with internal loops involving quarks of unequal masses. The hadronic contri-

bution to this decay can be reliably determined through its isospin conjugate decay mode $K^+ \rightarrow \pi^0 e^+ \nu_e$, and long distance effects have been shown to be negligible [1]. Thus, $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is highly sensitive to the parameters of the Cabibbo-Kobayashi-Maskawa quark mixing matrix, and may provide an unambiguous determination of $|V_{td}|$, once the mass of the top quark is known. The predicted branching ratio [2] from the standard model is in the range $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \Gamma(K^+ \rightarrow \pi^+ \nu \bar{\nu})/\Gamma(K^+ \rightarrow \text{all}) = (0.6-6) \times 10^{-10}$. Observation of this decay mode in excess of the predicted rate would suggest the existence of new phenomena [3].

Results have been reported [4] from our study of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the kinematic region above the $K^+ \rightarrow \pi^+ \pi^0$ ($K_{\pi 2}$) peak (region 1). The π^+ from $K_{\pi 2}$ decay has a kinetic energy, momentum, and range in plastic scintil-

*Present address: Department of Physics, Princeton University, Princeton, NJ 08544.

†Deceased.

‡Present address: Center for Particle Astrophysics, University of California, Berkeley, CA 94720.

§Present address: Department of Physics, Cornell University, Ithaca, NY 14853.

||Present address: Physics Department, National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan.

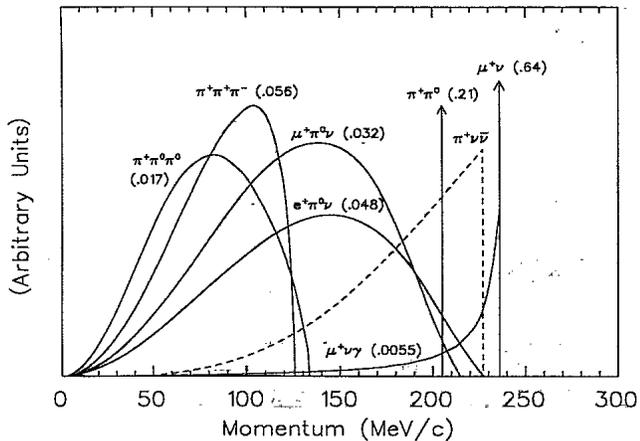


FIG. 1. Charged-track momentum distribution of the top seven decay modes of the K^+ . The branching ratio for each mode is indicated in parentheses. The dashed line shows the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ spectrum.

lator of 108 MeV, 205 MeV/c, and 30 cm, respectively. In this paper, we report our first results of a search in the region below the $K_{\pi 2}$ peak (region 2). Although region 2 is susceptible to additional background sources, it has larger potential acceptance than region 1 since the available phase space is more than twice as large and the loss of pions due to nuclear interactions in the detector is smaller at lower pion energies. A measurement in region 2 would help to determine the spectrum of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and region 2 has better sensitivity than region 1 to certain kinds of new physics, such as new tensor or scalar interactions, and production of massive, weakly interacting neutral particles ($150 < M_{X^0} < 250 \text{ MeV}/c^2$) [5]. For example, the production cross section of Majorons [6] is enhanced in the kinematic region below the $K_{\pi 2}$ peak. The previous experimental upper limit on the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ branching ratio using region 2 was 9.4×10^{-7} (90% C.L.) [7].

The momentum distribution of charged particles in K^+ decays at rest is shown in Fig. 1 for the seven most probable branches, along with $K^+ \rightarrow \pi^+\nu\bar{\nu}$. After $K^+ \rightarrow \mu^+\nu_\mu$ ($K_{\mu 2}$) and $K^+ \rightarrow e^+\nu_e$ decays are eliminated by kinematics, all the remaining single charged-track decay modes contain photons, except for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. Efficiency for detecting photons is limited by photonuclear interactions and constrains the extent to which the copious background process $K_{\pi 2}$ can be rejected. Therefore our search for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ has excluded the kinematic region of the $K_{\pi 2}$ monochromatic peak. The remaining phase space of interest is divided into region 1, between the $K^+ \rightarrow \pi^+\pi^0$ and $K^+ \rightarrow \mu^+\nu_\mu$ peaks, and region 2, between the $K^+ \rightarrow \pi^+\pi^0$ peak and the end point of the $K^+ \rightarrow \pi^+\pi^0\pi^0$ spectrum. In region 2, the only background processes from kaon decays involving charged pions are $K^+ \rightarrow \pi^+\pi^0\gamma$, the rare and as yet unseen decay [8] $K^+ \rightarrow \pi^+\gamma\gamma$, and those $K_{\pi 2}$ decays in which the π^+ loses some of its energy through nuclear interactions in the detector material. The latter can be rejected by detecting the interaction products or a kink in the π^+ track. Generally, backgrounds in region 2 can be dealt with via photon vetoing, kinematic analysis, and particle

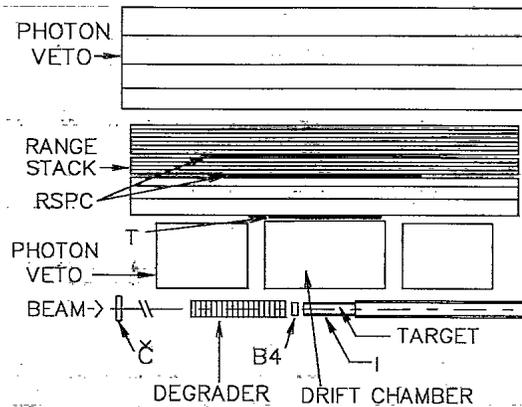


FIG. 2. Schematic side view showing the cross section of the upper half of the E787 detector.

identification using the decay chain $\pi^+ \rightarrow \mu^+\nu_\mu$ followed by $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ ($\pi \rightarrow \mu \rightarrow e$).

The experiment was performed at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. Details of the detector, shown schematically in Fig. 2, are described elsewhere [9]. An 800 MeV/c K^+ beam passed through a BeO degrader and a beam counter system, and stopped in a finely segmented target of plastic scintillating fibers. Typically 2×10^5 kaons per 1.4-s AGS pulse stopped in the target, which was surrounded by a cylindrical drift chamber providing an average total momentum resolution in the 1-T axial magnetic field of 3% at 200 MeV/c for charged decay products from the target. The fiducial region of about 2π sr was defined by plastic scintillation trigger counters (I and T counters) located at the inner and outer radii of the drift chamber. Pions stopped in a cylindrical array of plastic scintillation counters (range stack), where kinetic energy and range were measured. The range stack was divided in 24 azimuthal sectors and 14 radial layers. The first three layers (A, B, and C counters, in order of increasing radius) were 7.6, 5.7, and 3.8 cm thick, respectively; the remaining layers were 1.9 cm thick. Phototube signals from the range stack counters were recorded with 500-MHz transient digitizers (TD's) to detect the $\pi \rightarrow \mu \rightarrow e$ decay chain. The path of the π^+ was almost entirely in active material, which facilitated the measurement of the π^+ kinetic energy and detection of nuclear interactions. To veto events with photons, the outermost part of the detector, covering nearly 4π sr, consisted of a 12-14 radiation length lead-plastic scintillator sandwich calorimeter [10].

A multilevel trigger was used to select $K^+ \rightarrow \pi^+\nu\bar{\nu}$ candidates. The incoming K^+ was identified by a hit in a Čerenkov counter and its decay was signaled by a delayed coincidence between an I counter and the Čerenkov counter. Charged particles were required to trigger the T and A counters of a range stack sector and to stop at a radial depth between 7.6 and 19 cm from the T counter, in order to eliminate long-range $K_{\mu 2}$ and short-range $K^+ \rightarrow \pi\pi\pi$ decays. Vetoing events with photon hits in the calorimeter suppressed $K_{\pi 2}$, $K^+ \rightarrow \pi^0\mu^+\nu_\mu$, and $K^+ \rightarrow \pi^0e^+\nu_e$ decays. The main backgrounds surviving at this stage were $K^+ \rightarrow \mu^+\nu_\mu\gamma$ decays in which

the photon was undetected, and $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays in which a pion interacted in the first 7.6 cm of the range stack producing a secondary product that extended the track beyond 7.6 cm. At the next trigger level, $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays were suppressed by rejecting extra tracks using the number of hit elements in the target. A photon cut in the range stack outside the charged-track region was also applied. At the third trigger level, $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ and $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays were further suppressed by a fast algorithm requiring evidence for a $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay in the TD data of the outermost hit range-stack layer. The final trigger rate was a few Hz. A total of 5.3×10^{10} stopped K^+ 's were accumulated.

In the initial stage of off-line analysis, a single charged track was required in the target, drift chamber, and range stack. Cuts on extra activity in coincidence with the charged track were applied in the target, range stack, and lead-scintillator sandwich counters to eliminate events with photons as well as additional tracks. Tight constraints were applied to the energy deposition pattern of the outgoing track in the target. This was especially important to suppress $K_{\pi 2}$ events with π^+ nuclear interactions. The TD pulse shapes from both ends of the range-stack stopping counter were examined by a detailed fit for a second pulse consistent with a 4-MeV muon from the $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay. An electron signal from the subsequent $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ decay originating from the stopping region was also required. This tagging eliminated lepton tracks as well as pions undergoing nuclear absorption. The kinematic consistency among the momentum, kinetic energy, and range also served to suppress these backgrounds. Events with beam pions that scattered into the range stack and kaon in-flight decays were suppressed by requiring a delayed coincidence in the segmented target between the signals identified as K^+ and π^+ . Beam pions were also suppressed by detecting extra activity in a Čerenkov counter and in a plastic scintillation counter ($B4$) in front of the target at the time of the track in the range stack.

In the final stage of analysis, several additional types of backgrounds were identified and suppressed. The most prominent was due to $K_{\pi 2}$ decay with the π^+ interacting in the target elements assigned to the K^+ , hiding the extra energy. In particular, if the initial π^+ direction was along the beam axis, photons had a greater probability of escaping detection through the beam hole. Those events were suppressed by a cut on extra energy in active elements along the beam axis at the time of the π^+ . To detect extra energy in the K^+ elements in the target, a cut based on consistency between the range of the K^+ in the target as determined by finding the decay vertex using the drift chamber track, and the ranges inferred by the energy loss of the K^+ in the $B4$ counter and in the target, was applied. Remaining background from $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ decays was eliminated by tighter constraints on $\pi \rightarrow \mu$ tagging determined from a study of this mode using a calibration data sample. The third source of background identified was due to $K_{\pi 2}$ decays where the π^+ scattered in an end plate of the drift chamber; these were eliminated by applying cuts on the track position at the outer wall of the drift chamber as mea-

TABLE I. Acceptance factors. Each table entry represents the acceptance from a number of related cuts.

Category	Acceptance
Solid angle	0.36
π^+ Spectrum	0.30
π^+ nuclear absorption	0.75
π^+ decay in flight	0.92
$K^+ \rightarrow \pi^+$ delayed coincidence	0.71
Trigger efficiency	0.61
Offline reconstruction	0.62
$\pi^+ \rightarrow \mu^+$ TD tagging	0.50
$\mu^+ \rightarrow e^+$ TD tagging	0.75
π^+ kinematic consistency	0.84
Extra activity in the target	0.70
Accidental vetoes	0.59
Net acceptance	0.0026

sured in the drift chamber and the range-stack counters. Each cut was obtained by independent background study rather than by reference to individual candidate events. The expected background from all the sources mentioned was approximately one event or less for the entire data sample.

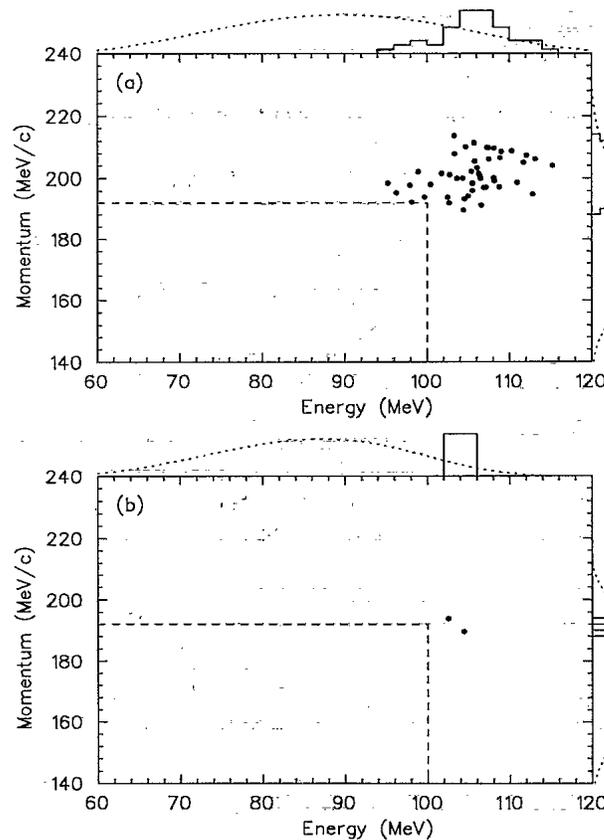


FIG. 3. (a) Momentum vs kinetic energy for events satisfying the selection criteria (see text) and (b) having, in addition, measured range $R_\pi < 27$ cm. The dashed rectangle indicates the search region for $K^+ \rightarrow \pi^+ \nu$. The dotted curves on the projection axes indicate the standard model spectrum for this process, folded with experimental resolution and acceptance.

Acceptance for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ was measured using samples of $K_{\mu 2}$ and $K_{\pi 2}$ events, and events where beam pions scattered into the range stack, which were collected simultaneously with the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data. A Monte Carlo simulation was used to determine the geometrical acceptance and the loss of π^+ 's due to nuclear absorption and in-flight decay. The kaon flux was determined from the number of $K_{\mu 2}$ decays observed. This number was consistent with the measured number of stopped K^+ 's in the target, confirming the validity of the geometric acceptance in the Monte Carlo simulation. To test the nuclear absorption and in-flight decay simulation, the $K_{\pi 2}$ branching ratio was measured. The value obtained was 0.215 ± 0.005 , where the error is statistical, and is consistent with the established value [11] of 0.2117 ± 0.0016 . Acceptance factors for groups of cuts are summarized in Table I. Background rejection in region 2 required tighter cuts than in region 1 [4], resulting in a slightly smaller net acceptance of 0.0026. The statistical uncertainty is less than 2.5% for all items in Table I; the estimated total uncertainty is 10%.

Figure 3(a) shows the charged-track momentum versus kinetic energy for events satisfying the selection criteria above; Fig. 3(b) shows the same distribution with the additional requirement that the measured range be less than 27 cm. The dashed rectangle indicates the search region for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ($T_{\pi^+} < 100$ MeV, $P_{\pi^+} < 192$ MeV/c, and $R_{\pi^+} < 27$ cm). There are no events in the search region. In both Figs. 3(a) and 3(b), events outside of the search region are consistent with $K_{\pi 2}$ decays in which the photons were not observed.

Based on no observed events after energy, momentum, and range cuts, we obtain a 90% confidence level upper limit of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.7 \times 10^{-8}$, assuming a standard model spectrum. This is a factor of 55 improvement on the previous search [7] in this kinematic region. As reported in Ref. [4], combining this result with the limit in region 1, a 90% confidence level upper limit of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 5.2 \times 10^{-9}$ is obtained.

Branching ratio upper limits (90% C.L.) can be extracted for some physics processes beyond the standard model. A Monte Carlo simulation of these processes provided the necessary corrections to the acceptance. For the production of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ through a scalar or ten-

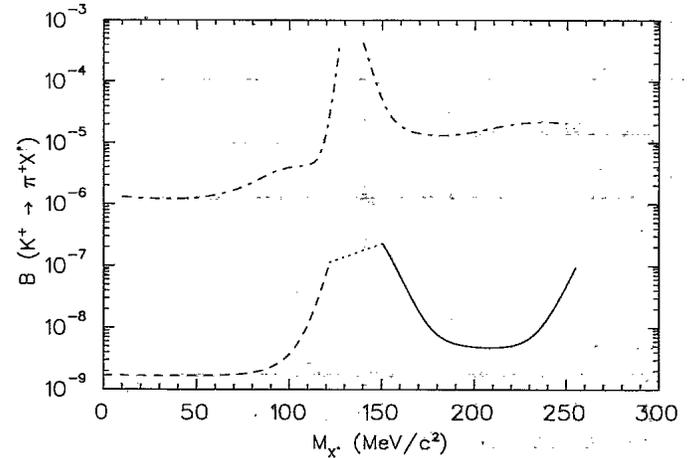


FIG. 4. 90% C.L. upper limit for $B(K^+ \rightarrow \pi^+ X^0)$ as a function of M_{X^0} , the mass of the recoiling system, along with previous results from this experiment. The dashed, dotted, and full lines are from Ref. [4], Ref. [12], and this analysis, respectively. The dashed-dotted line shows the previous result from Ref. [13].

tor interaction, the limits are 1.8×10^{-8} and 1.0×10^{-8} , respectively, for region 1 and region 2 combined. Region 2 has an order of magnitude more sensitivity than region 1 for these processes and therefore is the main contributor to these limits. This measurement is also sensitive to $K^+ \rightarrow \pi^+ X^0$, where X^0 is a hypothetical weakly interacting particle (or system of particles). Figure 4 shows limits on $B(K^+ \rightarrow \pi^+ X^0)$ together with the previous limits from Ref. [4], assuming X^0 has infinite lifetime. In the region of $M_{X^0} \sim M_{\pi^0}$, the limit is derived from our reported limit on the process $\pi^0 \rightarrow \nu \bar{\nu}$ [12]. Also shown is the previous result covering the range $0 < M_{X^0} < 250$ MeV/c² [13].

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