Search for the Decay $K^+ \rightarrow \pi^+ \mu^+ e^-$

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We report here on a search for the lepton-family-number–violating decay $K^+ \rightarrow \pi^+ \mu^+ e^-$. We found no evidence for this decay mode and we establish an upper limit on its branching ratio of 1.1×10^{-9} at the 90% confidence level (C.L.) for a uniform phase-space decay distribution. We also use this result to establish an upper limit for the branching ratio of the decay $\pi^0 \rightarrow \mu^+ e^-$ of 7.8×10^{-8} (90% C.L.).

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The level to which lepton-family number (LFN) is conserved is one of the outstanding issues of particle physics. Conservation of this quantity was hypothesized in the 1950's[1] and is now incorporated into the standard model. More recently, however, theoretical models addressing issues not resolved by the standard model have suggested that LFN may be violated at levels observable with present technology.[2,3] For many of these models, the decays $K_L^0 \rightarrow \mu e$ and $K^+ \rightarrow \pi^+ \mu^+ e^-$ are good candidates for such observations. For example, while violating LFN, these decays conserve "generation" number, as defined by Cahn and Harari,[3] and thus may be less inhibited than other processes, e.g., $\mu \rightarrow eee$, $\mu^+ A \rightarrow e^+ A$, or $\mu \rightarrow e\gamma$. New measurements of $K_L^0 \rightarrow \mu e$ have recently been published.[4] We are reporting in this paper the first results of a new search for the decay $K^+ \rightarrow \pi^+ \mu^+ e^-$.

The experiment, performed at the Brookhaven National Laboratory's Alternating Gradient Synchrotron, employed a two-magnet spectrometer system situated in a 5.8-GeV/c unseparated beam of approximately 5×10^6 K^+ and a mixture of 1×10^8 π^+ and protons per machine pulse of about 1-s duration. The detector, previously described in Ref. 5, is shown in Fig. 1. Also shown are the trajectories from a simulated $K^+ \rightarrow \pi^+ \mu^+ e^-$ decay originating in the 5-m-long, evacuated decay volume upstream of the magnet M1. M1 deflected positively charged particles to the right and negatively charged particles to the left for the purposes of removing them from the beam region and directing them to the sides of the apparatus specifically designed for the respective particle identification. Momentum measurement was accomplished by the four proportional-wire-chamber packages, P1–P4, situated around the spectrometer magnet M2. The momentum resolution of this configuration measured in GeV/c was $\sigma_P \approx 0.01 P^2$, where P, the momentum of the decay products, ranged from 0.6 to 4 GeV/c.

Correct particle identification of electrons on the left side of the apparatus and pions and muons on the right side was critical in reducing backgrounds. On the left, threshold Čerenkov counters Č1L and Č2L were filled with hydrogen gas at atmospheric pressure. For electron detection they had an average yield of 2.2 photoelectrons. For muon detection their threshold was 6.3 GeV/c.

Following the P4 proportional chamber was a Pb-scintillator shower counter.[6] It presented a total of 11.4 radiation lengths to incoming particles, and was segmented into two vertical, 24 horizontal, and three longitudinal sections. With the pulse height of every cell recorded for each event, the shower evolution for each track could be observed. In the analysis of the data dis-

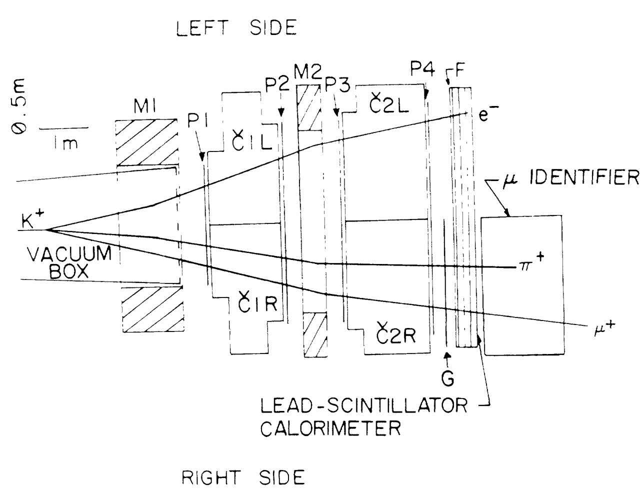

FIG. 1. Plan view of the apparatus. M1 and M2 are spectrometer magnets, P1–P4 are proportional wire chambers, and Č1L–Č2R are Čerenkov counters.

TABLE I. Particle-identification efficiencies.

	Č1	Č2	Shower	μ identifier	Total
π^+	0.99	0.99	0.96	⋯	0.94
μ^+	0.99	0.99	>0.99	0.98	0.95
e^-	0.90	0.90	0.99	⋯	0.80
e^+	0.98	0.97	0.99	⋯	0.94

cussed here, however, only information on the total energy deposition was used.

Particle identification on the right side was performed in a similar fashion, except that the Čerenkov counters Č1R and Č2R contained carbon dioxide at atmospheric pressure to ensure good electron rejection efficiency. The average yield for electrons was approximately 6 photoelectrons, and the muon threshold was 3.6 GeV/c.

Behind the shower detector on the right side was a μ identifier consisting of eight packages of proportional tubes interspersed between 9-cm-thick steel plates. Each package contained one vertically and one horizontally oriented plane of tubes with an effective wire spacing of 0.65 cm. Muons of momentum 0.6 GeV/c, the minimum momentum expected for $\pi\mu e$ events, penetrated the first four plates before reaching the end of their range, while muons of momentum above 1.1 GeV/c passed through the entire array.

Determination of the probabilities of misidentification and efficiencies was made with particles of known identities from the decays $K^+ \to \pi^+\pi^+\pi^-$ (tau decays) and $K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-\gamma$ (Dalitz decays) in the running environment. The results of those measurements are summarized in Tables I and II.

In front of the shower counter was a plane of scintillation counters, F, extending across the entire width of the shower counter, and a plane, G, extending across the right side. These counters, segmented horizontally and vertically in the same manner as the shower counter, were used for triggering purposes.

For the decay mode $K^+ \to \pi^+\mu^+e^-$, the detector was triggered by a coincidence between two sets of appropriately correlated F and G counters, $2(\mathrm{F}\cdot\mathrm{G})$, a potential muon track of at least four plates deep into the muon array, and observation of at least 0.4 photoelectrons in both Č1L and Č2L. For calibration a tau trigger was implemented in which the left-side requirement was a single F counter, and on the right was $2(\mathrm{F}\cdot\mathrm{G})$. Because of the large number of tau triggers, typically 10^5 per machine pulse, this trigger was prescaled by a factor of 8192. For calibration and normalization purposes a πee trigger was created in which the right-side requirement was $2(\mathrm{F}\cdot\mathrm{G})$ in coincidence with both Č1R and Č2R, and the left-side requirement was a Č1L, Č2L coincidence. This trigger, sensitive to Dalitz decays, was prescaled by a factor of 8. With the above triggers enabled simultaneously, the apparatus was triggered approximately 120 times per machine pulse, with a total of 8×10^7 triggers recorded. The efficiency of the triggers was studied by a series of runs with trigger elements removed one at a time.

Data analysis proceeded in a tiered fashion with successively more stringent kinematic and particle-identification requirements imposed at each layer. Potential events were first selected as those which had one and only one reconstructed track on the left and at least two on the right side of the apparatus in an accepted fiducial region. These tracks were required to emanate from a common vertex where the square root of the sum of the squares of the distances of the tracks, S, to a common point was less than 10 cm (S for K^+ decays has a mean value of 0.9 cm and a standard deviation of 0.5 cm, independent of decay mode). Variables describing the kinematics of the parent particles were calculated, and loose cuts applied to the angles and momentum of the reconstructed trajectory and to the position of the decay point. These cuts were loose enough to pass a significant portion of events with unmeasured neutrals (e.g., Dalitz decays).

The particle-identification system required all detectors to agree on the identification of the species of the daughter particles. Events with ambiguous responses were discarded.

For all of these cuts, indeed for every stage of the analysis, comparison was made between Monte Carlo simulations and data from tau and Dalitz decays to yield an understanding of efficiencies and possible biases. Monte Carlo and data distributions were compared and found to be consistent.

With tau events used as a template, distributions of reconstructed K^+ momentum, position, and angles at the production target could be formed. For this purpose the tau events were required to have $S<3$ cm, unambiguous particle identification, and reconstructed invariant mass within 15 MeV/c^2 of the kaon mass (the standard deviation on the reconstructed mass from taus was $\sigma \approx 3.7$ MeV/c^2). These distributions were then used to construct probability distributions for the subsequent analysis. With use of the template distributions, the likelihood for a given value, x, of a variable was defined as the ratio of the number of events in the bin at the value x to the total number of events in the distribution of the variable. With probability distributions so

TABLE II. Particle-misidentification probabilities.

Misident.	Č1	Č2	Shower	μ identifier	Total
π^- as e^-	0.002	0.002	0.14	⋯	6×10^{-7}
μ^- as e^-	0.002	0.002	<0.05	⋯	$<2\times10^{-7}$
e^+ as π^+	0.02	0.03	0.14	⋯	8×10^{-5}
e^+ as μ^+	0.02	0.03	0.14	<0.01	$<8\times10^{-7}$
π^+ as μ^+	⋯	⋯	⋯	0.04	0.04

defined, the likelihood of the observed variable for each candidate $\pi\mu e$ event was evaluated. The logarithm of the total likelihood was then calculated as the sum of the logarithms of the likelihoods of the different variables. A final cut was made at that value of the logarithm of the likelihood which accepted 90% of the tau events. Monte Carlo calculations indicated a similar acceptance for $\pi\mu e$ events.

Our results are displayed as scatter plots of S versus the invariant mass of the reconstructed three-charged-particle final state M. Figure 2 shows such a plot for taus with designation of a signal region for both parameters. The corresponding plot for the $K^+ \to \pi^+\mu^+e^-$ candidates is shown in Fig. 3. The signal region in M has been expanded, as prescribed by the Monte Carlo calculation, by 60% to account for the degradation in resolution due to the increased kinetic-energy liberation of this mode compared to taus. There are no events in the signal region. The nearest event consistent with a good vertex has an invariant mass of 467 MeV/c^2, 4.5 standard deviations away from the K^+ mass. Those events with mass near 400 MeV/c^2 are consistent in number and distribution with misidentified taus and taus with subsequent decay of one or more pions. Those at higher mass and large S are due to random association of hits and tracks in an event.

To compute the limit for the branching ratio of $K^+ \to \pi^+\mu^+e^-$ we normalize to Dalitz decays. This mode was chosen because the trigger requirement of light in Č1L and Č2L was common to it and to the decay of interest.[7] Details of the characteristics of the Dalitz-decay data samples are discussed in Ref. 5. Candidate Dalitz decays were subjected to the geometric, kinematic, and particle-identification cuts described above, with the exception of the likelihood requirements. Our 90%-confidence-level limit is then given by the following expressions:

$$B(K^+ \to \pi^+\mu^+e^-) = B(\text{Dalitz}) \frac{N(\pi\mu e)}{N(\text{Dalitz})} \frac{G(\text{Dalitz})}{G(\pi\mu e)} C .$$

$B(K^+ \to \pi^+\mu^+e^-)$ is the branching ratio for the decay $K^+ \to \pi^+\mu^+e^-$. B(Dalitz) is the combined branching ratio for the decay chain $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$; $B(\text{Dalitz}) = (2.54 \pm 0.07) \times 10^{-3}$. $N(\pi\mu e)$ is the 90%-confidence-level upper limit on the observed number of events; $N(\pi\mu e) = 2.3$. N(Dalitz) is the number of observed Dalitz events (including the prescaling factor) that passed the kinematical cuts, and that reconstructed without the γ ray to a mass >350 MeV/c^2. G(Dalitz) and $G(\pi\mu e)$ are the geometrical acceptances for the two decay modes as determined by Monte Carlo calculations; C is the product of correction factors that account for the effect of the likelihood cut (1.11), the contamination from other decay modes to the normalizing sample (1.04), the difference in particle-identification efficiency between muons and positrons (0.99), and the muon trigger efficiency (1.31). The data presented here were collected in two separate runs. The magnetic field in M2 during the first run was 30% lower because of a failure in two of its eight coils. For the first run we have $N(\text{Dalitz}) = (3.03 \pm 0.04) \times 10^5$, $G(\pi\mu e) = 2.10 \times 10^{-2}$, $G(\text{Dalitz}) = 2.43 \times 10^{-3}$, and $C = 1.55 \pm 0.05$, and the

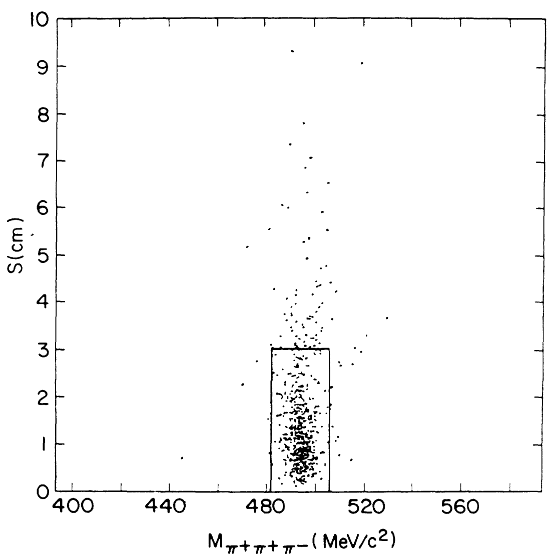

FIG. 2. S vs mass plot for taus. The signal region is designated by the rectangle for $483 < M_{\pi\pi\pi} < 505$ MeV/c^2 and $S < 3$ cm, where S is the square root of the sum of the squares of the distances of the tracks to a common vertex. There are 873 events in the plot.

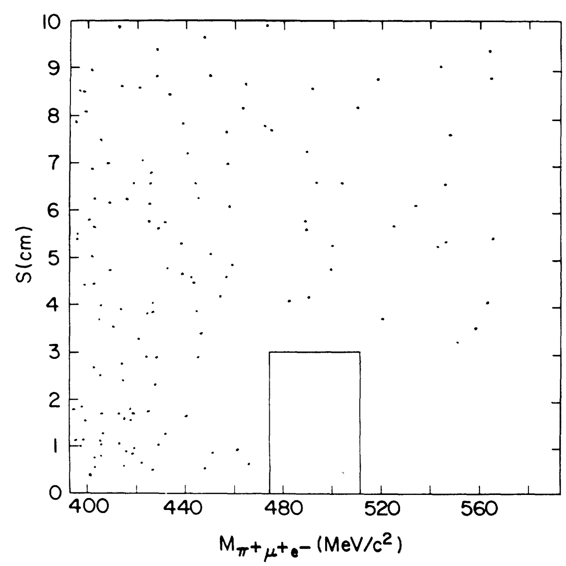

FIG. 3. S vs mass plot for $\pi\mu e$ candidates. There are 133 events in the plot. The signal region is designated by the rectangle for $476 < M_{\pi\mu e} < 512$ MeV/c^2 and $S < 3$ cm.

second run, $N(\text{Dalitz}) = (4.55 \pm 0.04) \times 10^5$, $G(\pi\mu e) = 1.94 \times 10^{-2}$, and $C = 1.46 \pm 0.05$. $G(\text{Dalitz}) = 1.59 \times 10^{-3}$, The $\pi\mu e$ acceptance was calculated under the assumption of a uniform phase-space distribution. That of Dalitz decays was calculated with use of a theoretical distribution with a constant form factor.[8] We combine the results from both runs to obtain $B(K^+ \to \pi^+ \mu^+ e^-) < 1.1 \times 10^{-9}$ at the 90% confidence level. The systematic error in the determination of the ratio of acceptances $G(\text{Dalitz})/G(\pi\mu e)$ is the principal source of uncertainty, and is estimated by Monte Carlo simulations to be less than 10%.

Since there are no candidates for $K^+ \to \pi^+ \mu^+ e^-$, we see no events of the types $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \mu^+ e^-$. We can use this fact to establish an upper limit on the branching ratio for the decay $\pi^0 \to \mu^+ e^-$. The acceptances for this decay chain in the two runs were 1.5×10^{-3} and 1.2×10^{-3}, respectively. Using the method described above we obtain an upper limit for $B(\pi^0 \to \mu^+ e^-)$ of 7.8×10^{-8} (90% confidence level).

The upper limit on the branching ratio for $\pi^0 \to \mu^+ e^-$ is the first to be reported directly by the group making the measurement and is comparable to the previously determined value.[9] On the basis of the published decay rates of neutral and charged pions,[10] this result implies that the ratio of the magnitude of the matrix element for $\pi^0 \to \mu^+ e^-$ to that for $\pi^+ \to \mu^+ \nu$ is less than 5.

The result on $B(K^+ \to \pi^+ \mu^+ e^-)$ represents an improvement of a factor of 4.4 on the previously published limit.[11] In the model of Cahn and Harari[3] which postulates a new interaction with neutral gauge bosons connecting fermions of different generations, if the new coupling strength is set equal to that of the weak interaction, our results place a lower limit of 27 TeV/c^2 on the mass of such bosons.

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