Improved Limit on the Branching Ratio of $K^+ \rightarrow \pi^+ \mu^+ e^-$

A. M. Lee,(5) C. Alliegro,(5) C. Campagnari,(5),(a) V. Chaloupka,(4) P. S. Cooper,(2) J. Egger,(3) H. A. Gordon,(1) N. J. Hadley,(5),(b) W. D. Herold,(3) E. A. Jagel,(4),(c) H. Kaspar,(3) D. M. Lazarus,(1) H. J. Lubatti,(4) P. Rehak,(1) M. E. Zeller,(5) and T. Zhao(4)

(1)*Brookhaven National Laboratory, Upton, New York 11973*
(2)*Fermi National Laboratory, Batavia, Illinois 60510*
(3)*Paul Scherrer Institute (Swiss Institute for Nuclear Research), CH-5234 Villigen, Switzerland*
(4)*Department of Physics, University of Washington, Seattle, Washington 98195*
(5)*Department of Physics, Yale University, New Haven, Connecticut 06511*

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A search for the lepton-flavor number-violating decay $K^+ \rightarrow \pi^+ \mu^+ e^-$ has been conducted at the Brookhaven Alternating Gradient Synchrotron. No candidates have been found which would be consistent with this decay mode. An upper limit on the branching ratio is placed at 2.6×10^{-10}, which can be combined with our previous result to yield an upper limit of 2.1×10^{-10} at the 90% confidence level. A limit on the branching ratio for $\pi^0 \rightarrow \mu^+ e^-$ of 1.6×10^{-8} (90% C.L.) is also established.

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The standard model of QCD and electroweak interactions has had remarkable success in describing and predicting a wide variety of phenomena. In spite of this success, however, issues remain which cannot be addressed by the model alone, e.g., the origin of fermion masses, the number of lepton and quark generations, and the gauge hierarchy problem. Because of these limitations, extensions have been created which admit the possibility of flavor-changing neutral currents and muon-number-violating interactions.[1,2] Were these extensions valid, one might observe decays such as $\mu^+ \rightarrow e^+ e^+ e^-$, $\mu^+ \rightarrow e^+ \gamma$, $\mu^- A \rightarrow e^- A$, $K_L^0 \rightarrow \mu e$, and $K^+ \rightarrow \pi^+ \mu^+ e^-$. Thus in the early 1980s we and others began to search for these decays with improved sensitivity, and many new limits have been established.[3,4] In this paper we are reporting new results for a search for the decay $K^+ \rightarrow \pi^+ \mu^+ e^-$ ($K_{\pi\mu e}$).

Initial results from this experiment, and details of the detector and its operation, have been described in earlier publications.[4,5] Subsequent changes in the experiment included alterations in the collimation of the kaon beam near the production target, and an improved data-acquisition system incorporating microprocessors in Fermilab advanced-computer-program modules (ACP's),[6] and smart crate controllers[7] for our CAMAC system. These changes allowed us to increase the kaon flux by a factor of 2 with significantly reduced background. Figure 1 shows a schematic diagram of the apparatus. Approximately 10^7 kaons per machine pulse of about one-second duration, with momentum 6 GeV/c, entered the 5-m-long decay volume where about 10% decayed. Accompanying these kaons were a total of about 2×10^8 pions and protons. Decay-particle trajectories were deflected out of the beam region by the magnet $M1$, and their momentum determined by the magnet $M2$ in conjunction with multiwire proportional chambers (MWPC's) $P1$–$P4$. These chambers and all other detectors were deadened in the regions through which the beam passed. The resolution of this spectrometer system (in GeV/c) was $\sigma_P = 0.01P^2$, where P, the momentum of the decay products, ranged from 0.6 to 4.0 GeV/c.

Several decay modes of the K^+ can mimic $K_{\pi\mu e}$ if the species of the decay products are identified incorrectly, e.g., $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ (τ decays) where the π^- is identified as an electron and one of the π^+'s is taken for a μ^+, or $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow e^+ e^- \gamma$ (Dalitz decays) where the e^+ is mistaken for a π^+ and the π^+ for a μ^+. To avoid this the detector was divided into left and right sides, with different emphasis for particle identification on each. On the left, the side to which negative particles were deflected, electron detection with maximal pion re-

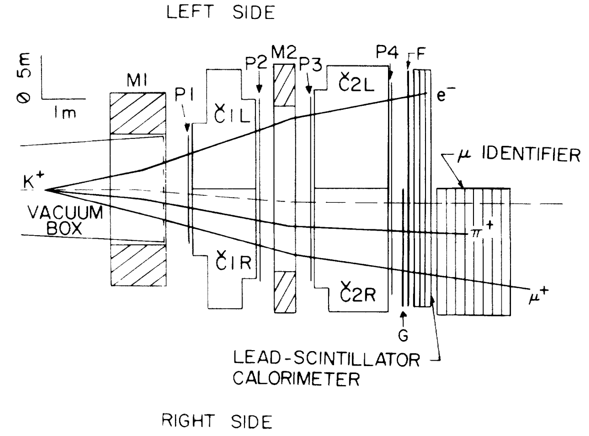

FIG. 1. Plan view of the apparatus. $M1$ and $M2$ are spectrometer magnets, $P1$–$P4$ are multiwire-proportional-chamber packages, $\check{C}1L$–$\check{C}2R$ and Čerenkov counters, and F and G are scintillation-counter hodoscopes. The dash-dotted line represents the 6-GeV/c beam line. Material was removed from the beam region of the shower detector and muon identifier.

jection was required. To achieve this, two hydrogen-gas Čerenkov counters $\check{C}1L$ and $\check{C}2L$, operated at atmospheric pressure, were employed in tandem. Since these counters were separated by the spectrometer magnet $M2$, common mode noise such as delta rays or low-energy electrons from photon conversions in the upstream material was minimized. The efficiency of the pair of counters for detecting electrons was about 85%, while the pion-misidentification probability was 2×10^{-5}.

Following the last MWPC was a segmented Pb-scintillator shower detector containing eleven radiation lengths of material, and segmented into two vertical, 24 horizontal, and three longitudinal sections.[8] Requiring energy deposition in this counter to be consistent with that of electrons increased the pion rejection of the left side by a factor of 6, averaged over all momenta, with a loss of only 5% in electron detection efficiency.

On the right side of the apparatus, correct identification of the π^+ and μ^+ was the design goal. To realize this, efficient rejection of positrons was necessary. Thus the right-side Čerenkov counters were filled with CO_2 also at atmospheric pressure, with their threshold just at the upper end of the muon momentum spectrum for $K_{\pi\mu e}$, at 3.7 GeV/c. With an average number of six photoelectrons, these counters were used in an OR mode and were 99.9% efficient at rejecting positrons. The shower counter provided a further, loosely constrained veto by rejecting tracks whose energy deposition was greater than three-quarters of their measured momentum. This raised the rejection factor to 99.97%, with an insignificant loss in efficiency for detecting pions. Following the shower counter was a muon detector consisting of eight modules of proportional tubes interspersed between 9-cm-thick steel plates.

Those particles not rejected as positrons, which had a track in the muon detector whose range was consistent with its measured momentum, were identified as muons. Those which had no such track were determined to be pions. The final identification efficiency was then 80% for muons, and 95% for pions.

The detection and rejection efficiencies of the system were determined by measuring the response of the various detectors to particles of known species originating from τ and Dalitz decays. To accumulate calibration muons, the beam magnets were turned off with the primary proton beam still impinging on the kaon production target. A sufficient number of muons then penetrated the beam shielding walls and passed through the muon detector to test triggering, detection, and software efficiencies.

All triggers required two particles on the right as determined by two pairs of appropriately correlated coincidences between the F and G scintillation-counter hodoscopes $[2(F\cdot G)]$. The $K_{\pi\mu e}$ trigger then required a potential muon track and a $\check{C}1L\cdot\check{C}2L$ coincidence with a threshold of 0.4 photoelectron in each counter. A τ trigger was implemented which required an F counter on the left side in coincidence with $2(F\cdot G)$. Because the τ trigger occurred at a rate of about 10^5 per machine spill it was prescaled by a factor of 8192. Finally, a $K^+\rightarrow\pi^+e^+e^-$ $(K_{\pi ee})$ trigger was created which required $\check{C}1L\cdot\check{C}2L$ and $\check{C}1R\cdot\check{C}2R$ coincidences with $2(F\cdot G)$. This trigger was also sensitive to Dalitz decays and was prescaled by a factor of 8.

Triggers occurred about 250 times per machine pulse, causing the addresses of struck wires and counters, pulse heights of the Čerenkov and shower counters, and timing information from the Čerenkov and hodoscope counters to be transferred to a CAMAC system. From there the data were transmitted to one of fifteen single-board computers (ACP nodes),[6] which buffered all events from a single pulse.

Within the nodes a preliminary scan of the number of struck wires and counters was made to determine that a reasonable probability existed that an event contained at least three tracks. If it did not, the event was discarded. For events which passed this cut, analysis proceeded wherein the quality of track reconstruction was evaluated and track momenta were determined. For those events containing only one track on the left and at least two on the right the rms distance of closest approach of three track combinations to a common vertex (S) was calculated. Events were retained which had at least three tracks of acceptable quality, and an S of less than 10 cm. S for K^+ decays at this stage of the analysis had a mean value of 1.8 cm and a FWHM of 2 cm, independent of decay mode. No particle identification was made at this stage. The analysis in the ACP nodes rejected approximately 95% of the triggers, leaving about 3×10^7 events to be recorded on magnetic tape.

Off line, the momenta and spatial parameters of the tracks were used to determine the trajectory of the incident kaon and to evaluate the hypothesis that it originated at the production target. Particle identification was also performed, and events were routed and recorded in appropriate "streams" constructed for the various decay modes.

Successfully reconstructed events are displayed in a plot of S versus the invariant mass of the decay products. Such a plot for a sample of events with three pions in the final state is displayed in Fig. 2(a), with lines drawn to delineate the signal region (3 standard deviations in invariant mass and 95% acceptance in S). One sees a clear signal of τ decays with invariant mass equal to that of the K^+ peaked toward small S. Events with the correct invariant mass but large S are mostly those for which one of the pions decayed to a muon in flight through the apparatus. Monte Carlo calculations represent these distributions well.

The equivalent plot for $\pi\mu e$ events, for the complete data sample, is shown in Fig. 2(b). Because of the increase in the kinetic energy released in this mode over

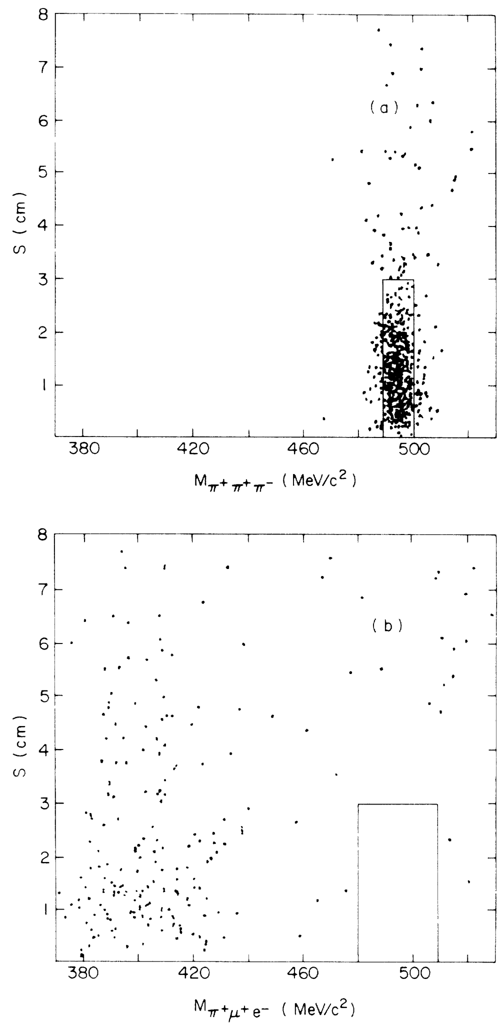

FIG. 2. S vs invariant mass for (a) τ decays and (b) $K_{\pi\mu e}$ candidates. The rectangular outlines are the signal regions as described in the text.

that of τ, the signal region must be enlarged. This was done by scaling up the signal region of Fig. 2(a) according to Monte Carlo calculations. As can be seen, the two events nearest to the K^+ mass, with acceptable S, have invariant masses of 474.9 and 512.5 MeV/c^2, 3.8 and 3.7 standard deviations away from the K^+ mass, respectively. Events below 450 MeV/c^2 result from τ decays with the π^- misidentified as an electron and a π^+ as a muon, those above are most likely Dalitz decays with a positron mistaken for a π^+, and those with large S are due to the association of random or mismeasured tracks. This distribution of backgrounds leads to a minimum in our signal region, as predicted by Monte Carlo simulations. Our Monte Carlo calculation predicts ~0.1 event in the signal region.

From the fact that we observed no events consistent with $K_{\pi\mu e}$ we can place an upper limit on the branching ratio for this mode. To do this we normalize to Dalitz decays since the triggers for this and the $K_{\pi\mu e}$ modes both required $\bar{C}1L \cdot \bar{C}2L$, and thus the ratio of their numbers is beam-rate independent. Selection of Dalitz-decay events, details of which have been described previously,[4] required the same track-, kinematic-, and particle-identification quality as other modes, an S less than 4 cm, but no requirement that the kaon trajectory originate from the target. Dalitz-decay events with an invariant mass of the πee greater than 350 MeV/c^2 were used for this normalization, and the relative acceptance between these and $K_{\pi\mu e}$ events was determined by Monte Carlo calculation (the theoretical distribution with a constant form factor was used for Dalitz decays,[9] and a phase space distribution for $K_{\pi\mu e}$).

The branching-ratio limit is calculated according to the following formula:

$$B(K_{\pi\mu e}) < B(\text{Dalitz}) \frac{N(K_{\pi\mu e}) G(\text{Dalitz})}{N(\text{Dalitz}) G(K_{\pi\mu e})} C ,$$

where B is the appropriate branching ratio [$B(\text{Dalitz}) = (2.54 \pm 0.07) \times 10^{-3}$];[10] N is the number of events [$N(K_{\pi\mu e}) = 2.3$ for a 90% confidence level, and $N(\text{Dalitz}) = 2.23 \times 10^6$]; G is the acceptance [$G(K_{\pi\mu e}) = 0.0167$, and $G(\text{Dalitz}) = 1.34 \times 10^{-3}$]; and C is a correction factor to account for differences in the efficiencies of the cuts for the two modes, contamination of the normalizing sample from other kaon decay modes, and differences in particle-identification efficiency between positrons and muons ($C = 1.26 \pm 0.10$). In addition to the uncertainty on C, we estimate a systematic uncertainty of 7% on the ratio of the acceptances of the two modes.

For the data set described in this paper we obtain a branching-ratio limit of $B(K_{\pi\mu e}) < 2.6 \times 10^{-10}$ at the 90% confidence level. This result can be combined with our previously published limit of 1.1×10^{-9} to yield an overall limit for our experiment of $B(K_{\pi\mu e}) < 2.1 \times 10^{-10}$ (90% C.L.). Calculating the acceptance for the decay $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \mu^+ e^-$ to be 1.09×10^{-3}, we use the same method to place an upper limit on $B(\pi^0 \rightarrow \mu^+ e^-) < 1.9 \times 10^{-8}$. When combined with our previous limit of 7.8×10^{-8}, this results in an overall limit of 1.6×10^{-8} (90% C.L.).

Our limit can be compared with the branching ratio for $K_{\mu 3}$, $B(K_{\pi\mu e})/B(K_{\mu 3}) < 6.4 \times 10^{-9}$. If there were a horizontal gauge interaction with purely vector coupling, and strength equal to that of the weak interaction, such as in the model of Cahn and Harari,[2] this ratio would imply a mass of greater than 39 TeV/c^2 for its gauge boson.

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(a)Present address: University of Chicago, Chicago, IL 60637.

(b)Present address: University of Maryland, College Park, MD 20742.

(c)Present address: CERN, Geneva, Switzerland.

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