Observation of the Decay $K^+ \to \pi^+ \mu^+ \mu^-$

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We have observed the rare decay $K^+ \to \pi^+ \mu^+ \mu^-$ and measured the branching ratio $\Gamma(K^+ \to \pi^+ \mu^+ \mu^-)/\Gamma(K^+ \to \text{all}) = [5.0 \pm 0.4(\text{stat}) \pm 0.7(\text{syst}) \pm 0.6(\text{th})] \times 10^{-8}$. We compare this result with predictions from chiral perturbation theory and estimates based on the decay $K^+ \to \pi^+ e^+ e^-$. [S0031-9007(97)04785-6]

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We report the observation of the rare decay $K^+ \to \pi^+ \mu^+ \mu^-$ and the measurement of the branching ratio $\Gamma(K^+ \to \pi^+ \mu^+ \mu^-)/\Gamma(K^+ \to \text{all})$. The electromagnetically induced semileptonic weak processes $K^+ \to \pi^+ l^+ l^-$ ($l = e, \mu$) have been the subject of considerable theoretical study for over 40 years [1]. Though gauge theory calculations in the free quark approximation [2] gave a result in rough agreement with the subsequent observation of $K^+ \to \pi^+ e^+ e^-$ [3], the inclusion of QCD corrections [1,4] showed this agreement to be fortuitous and established that these decays are, in fact, long-distance dominated. Ecker, Pich, and de Rafael [5] first applied the techniques of chiral perturbation theory (ChPT) to this problem, and most recent discussion has been conducted in this language [6]. In [5], the rate and dilepton invariant mass spectrum of $K^+ \to \pi^+ l^+ l^-$ are calculated in terms of a single unknown parameter, w_+. Consequently, this parameter also controls the ratio of rates $\Gamma(K^+ \to \pi^+ \mu^+ \mu^-)/\Gamma(K^+ \to \pi^+ e^+ e^-)$. Calculations of w_+ in various models [5,7] have ranged from 0.49 to 2.04.

In the first experiment able to probe this picture, Alliegro *et al.* [8] made a combined fit to the branching ratio and spectrum of $K^+ \to \pi^+ e^+ e^-$, obtaining $B(K^+ \to \pi^+ e^+ e^-) = [2.99 \pm 0.22(\text{stat}) \pm 0.14(\text{syst})] \times 10^{-7}$ and $w_+ = 0.89^{+0.24}_{-0.14}$. The value of w_+ determined from the branching ratio alone is 1.20 ± 0.04, a little more than 1σ above the value obtained from the simultaneous fit. Our previous search for the decay mode $K^+ \to \pi^+ \mu^+ \mu^-$ set a limit of $B(K^+ \to \pi^+ \mu^+ \mu^-) \leq 2.3 \times 10^{-7}$ (90% confidence level) [9]. The measurement of $B(K^+ \to \pi^+ \mu^+ \mu^-)$ allows further tests of the ChPT picture. $K^+ \to \pi^+ l^+ l^-$ decays are also of interest for the light they can shed on the closely related decays $K_S \to \pi^0 l^+ l^-$, which are important in isolating the contribution of direct CP violation in the decay $K_L \to \pi^0 l^+ l^-$ [10].

The experiment reported here was carried out at the Brookhaven Alternating Gradient Synchrotron from 1989 to 1991 using the E-787 apparatus described in Ref. [11]. An 800 MeV/c K^+ beam is tagged by a Čerenkov counter and stopped in a scintillating fiber target. Decay particles from the target are detected in nested cylindrical layers of trigger scintillators, a tracking drift chamber, a "range stack" of scintillator layers read out with 500-MHz transient digitizers (TD), and 14 radiation lengths of Pb-scintillator photon detector. Azimuthally, the trigger counters, range stack, and photon detector are divided into 6, 24, and 48 sectors, respectively. Both ends of the cylinder are instrumented with 12-radiation-length Pb-scintillator "end cap" photon detectors. The entire apparatus is in a 1-T solenoidal magnetic field.

In each 1.5-s beam spill, approximately 3×10^5 kaons enter the stopping target. Requiring a delay >1.5 ns between the entering and decay particles ensures that the kaons stopped in the target before decaying. The trigger then selects decays in which two or three charged particles reach the range stack with $|\cos\theta| < 0.5$ (θ is the polar angle with respect to the beam direction) and none

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penetrate beyond 14 cm at 90°. Events with more than 5 (10) MeV in the cylindrical (end cap) photon detectors or more than 5 MeV in the outer region of the range stack are eliminated by the trigger. These requirements are aimed at the major backgrounds: $K^+ \to \pi^+\pi^0$ or $K^+ \to \pi^0\mu^+\nu_\mu$, followed by $\pi^0 \to \gamma e^+e^-$ (Dalitz decay) or by $\pi^0 \to \gamma\gamma$ with $\gamma \to e^+e^-$; and $K^+ \to \pi^+\pi^+\pi^-$. In total, we accumulated about 6×10^6 triggers from 3×10^{11} stopped kaons.

We search these data for $K^+ \to \pi^+\mu^+\mu^-$ events using two experimental signatures analyzed in parallel. One signature requires complete reconstruction of the three-track $K^+ \to \pi^+\mu^+\mu^-$ events in the drift chamber and target. Not only can momentum conservation be ensured for such events, but particle identification techniques such as dE/dx measured in the drift chamber can be applied to all three tracks. The other signature uses the fact that the spectrometer, in which accepted charged tracks penetrate little material other than scintillator, is a hermetic detector of kinetic energy. The segmentation of the kaon stopping target allows separation of the kaon signal from the decay-product signals, and a $K^+ \to \pi^+\mu^+\mu^-$ event can be recognized by its total kinetic energy of 143 MeV, even if one of the tracks is not reconstructed outside the target. This "two-track" signature [12] is important because Monte Carlo simulation indicates that only 10% of $K^+ \to \pi^+\mu^+\mu^-$ events that pass the trigger have a third track that leaves the target.

The preliminary event selections for the two signatures are similar. First, reconstructed tracks are required to originate near the kaon track in the target. Next, no event is accepted having a track with momentum greater than the $K^+ \to \pi^+\mu^+\mu^-$ end point of 172 MeV/c—most other kaon decays have a higher-momentum track. Events with photons or showering electrons are rejected if they have energy deposited in the photon detectors or in range stack modules isolated from the charged tracks (typical threshold $\sim$ 1 MeV). To avoid excessive loss of acceptance from the high accidental rates in these detectors, only depositions within 1.0–3.5 ns of the charged tracks (depending on analysis and detector) are used. Further rejection of events with electrons comes from demanding that the total energy measured in the inner range-stack layers be less than 150 (120) MeV for the three- (two-)track analysis.

At this point, the major backgrounds are $K^+ \to \pi^+\pi^-e^+\nu$, $K^+ \to \pi^0\mu^+\nu$ with Dalitz decay, and $K^+ \to \pi^+\pi^+\pi^-$, the last of these entering only the two-track sample. Dramatic reduction of these backgrounds occurs when we require that two positively charged tracks reach the range stack. For the first two backgrounds, this requires that the positron reach the range stack, and all the electron identification techniques of both analyses can be brought to bear on it. It is difficult for both π^+'s in $K^+ \to \pi^+\pi^+\pi^-$ events to reach the range stack. If they do, the π^- is confined to the target, increasing the effectiveness of the final kinematic requirements.

For each track reaching the range stack, the momentum measured in the drift chamber can be combined with the kinetic energy measured in the range stack to give the mass of the particle. The rms resolution on this mass is 10–20 MeV/c^2 for pions and muons in the momentum range of interest. Both analyses reject electrons by requiring $m > 60$ MeV/c^2 for any tracks reaching the range stack.

The final requirements of the two analyses differ sharply. In the three-track analysis, $K^+ \to \pi^+\pi^-e^+\nu$ decays dominate the background. Some positrons are rejected by restricting the number of range-stack counters allowed on each track, further suppressing showers. To eliminate remaining background events with electrons or positrons, information from drift chamber dE/dx, dE/dx in the first layer of the range stack, and time of flight from the trigger counter to the range stack are combined into a likelihood whose acceptance and rejection are measured on samples of known $e^\pm$ and π^+ [13]. Requiring a 90%-confidence-level elimination of electrons results in a sample of 22 events. Figure 1 shows the total transverse momentum, $|\Sigma \mathbf{p}_T|$, calculated by extrapolating the three tracks back to the decay vertex and correcting for energy loss in the target, versus the three-track invariant mass of this sample. The assignment of π^+ or μ^+ is chosen to minimize $|\Sigma \mathbf{p}_T|$ (the mass enters only in corrections for propagation in the target), but π^+ and μ^+ are not otherwise distinguished. Monte Carlo simulation of $K^+ \to \pi^+\mu^+\mu^-$ indicates that about 80% of the events that remain after preliminary event selection should appear in the signal box, the smaller of the two boxes in the figure. There are 13 events in this box.

The background in the signal box is estimated by counting the number of events in a background box

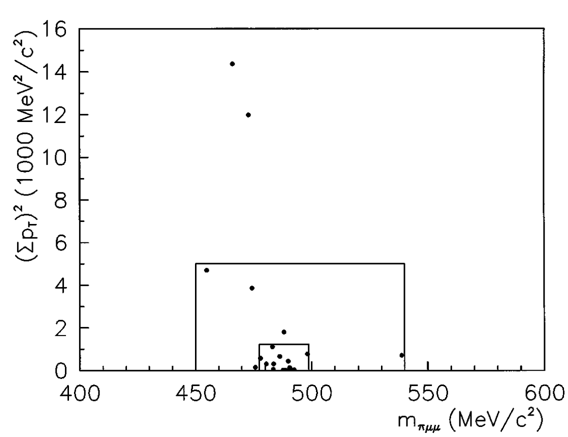

FIG. 1. Kinematics of final sample in the three-track analysis. $|\Sigma \mathbf{p}_T|$ is the total transverse momentum (near zero for signal), and $m_{\pi\mu\mu}$ is the three-track invariant mass ($\approx m_K$ for signal). The inner and outer boxes are for determining signal and background (see text). There are two events with $|\Sigma \mathbf{p}_T|^2 >$ 16 000 MeV$^2/c^2$.

surrounding the signal box (see Fig. 1) and using a Monte Carlo prediction of the ratio of background events in the two regions, taking into account the fraction of signal events outside the signal box. The background estimated this way is 2.4 ± 2.2 events. This is consistent with an estimate using trigger counter dE/dx, which is not an ingredient of the particle identification likelihood, to count events in the signal box with an e^+. It is also consistent with an absolutely normalized Monte Carlo calculation. The net signal from the three-track analysis is thus 10.6 ± 4.7 events.

The final requirements in the two-track analysis impose momentum conservation. For the small minority of events in the sample with three reconstructed tracks in the drift chamber, we demand that the vector sum of the momenta be less than 60 MeV/c. For the rest of the events, the expected energy of the third track and its angle in the plane transverse to the beam are calculated from the two reconstructed tracks, assuming $K^+ \rightarrow \pi^+ \mu^+ \mu^-$. Requiring that the "stub" of the third track seen in the target be within 0.9 radians of the expected direction rejects $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$, which has a missing neutrino. Requiring that the energy of the stub be within 25 MeV of its expected kinetic energy rejects both $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ and $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ because the π^- in these events usually deposits substantial energy after nuclear capture.

The total kinetic energy distribution of the final two-track sample is shown in Fig. 2. The large peak at about 135 MeV coincides with the Monte Carlo distribution for $K^+ \rightarrow \pi^+ \mu^+ \mu^-$. The discrepancy between the peak position and the expected 143 MeV results primarily from fibers in the target where energy deposits from the kaon hide the energy deposited by decay particles. Unrejected $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ events produce the smaller peak at 80 MeV. The background extending into the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ signal region is mostly due to $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays with additional energy released in π^- nuclear capture. To estimate the sizes of the signal and background, a function consisting of two Gaussians and a second-degree polynomial is fitted to the spectrum (see Fig. 2). The number of the signal events from the fit is 196.0 ± 16.7. The fitted number of background events in the interval $110 < E_{\mathrm{kin}} < 160$ is 25. Variations in the signal with the functional form assumed in the fit are included in the systematic error discussed below.

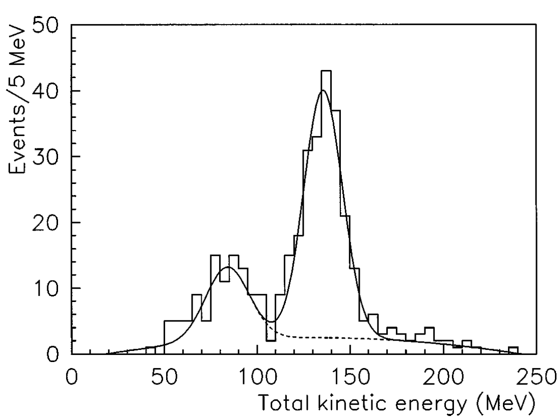

FIG. 2. Total decay-product kinetic energy of events surviving the two-track analysis. The peak at 135 MeV corresponds to the expected kinetic energy in $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay. The smooth curve is the fit to the spectrum with (solid) and without (dashed) the Gaussian term for the signal.

To confirm identification of the main peak in Fig. 2 as $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, the TD's are used to look for a $\pi^+ \rightarrow \mu^+$ decay in the last counter on each track. This allows an estimate of the number of $\pi^+ \mu^+$ and $\pi^+ \pi^+$ pairs in the final sample in different regions of the energy distribution. The fraction of $\pi^+ \mu^+$ pairs in the signal region (110 to 160 MeV) is consistent with the ratio of fitted signal and background, and the peak attributed to $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ is mostly $\pi^+ \pi^+$ pairs. Monte Carlo studies show that the number of $\pi^+ \mu^+$ pairs in the signal region due to a decay in-flight of one of the pions in a $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decay is negligible. The other K^+ decay involving a $\pi^+ \mu^+$ pair is $K^+ \rightarrow \pi^+ \pi^- \mu^+ \nu$. The maximum total kinetic energy of the charged particles in this decay is 108.9 MeV and the number of these events in the signal region is estimated to be less than five.

The number of stopped kaons is determined by normalizing a sample of $K^+ \rightarrow \mu^+ \nu$ events, taken simultaneously with the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ sample, to the known branching ratio. Several possible systematic errors in the final branching ratio cancel via this procedure. To estimate the acceptance for $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, Monte Carlo simulation is used for kinematic factors and data are used for accidental losses, particle identification, and timing requirements. The simulation used the matrix element from ChPT [5] with the parameter $w_+ = 0.89$ [8]. Both analyses have acceptance in the region of dimuon invariant mass from $m_{\mu\mu} = 211$ MeV/c^2 (the end point) to $m_{\mu\mu} \approx 300$ MeV/c^2 (where the π^+ can barely reach the range stack).

The trigger efficiency varied from 5.3% to 9.3% over the course of three years [14]. The full acceptance for the trigger and three-track analysis varied from 8.3×10^{-4} to 9.6×10^{-4} over the three years of data. The branching ratio from the three track analysis is $[3.9 \pm 1.7(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \times 10^{-8}$. The estimated systematic error is dominated by uncertainty in the acceptance, obtained by comparing a parallel measurement of the $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ branching ratio with the world average branching ratio.

The full acceptance of the two-track search, including trigger efficiency, varied from 0.011 to 0.017, resulting in a branching ratio of $[5.1 \pm 0.4(\mathrm{stat}) \pm 0.7(\mathrm{syst})] \times 10^{-8}$. The systematic error includes the uncertainty in the background shape, found by variations in the functional form used in the fit, and a catalog of uncertainties affecting the acceptance, the largest being the thickness of the trigger counters.

Taking into account the fact that the systematic errors in normalization and acceptance are correlated between the two analyses, we combine these two consistent results to give $B(K^+ \rightarrow \pi^+ \mu^+ \mu^-) = [5.0 \pm 0.4(\text{stat}) \pm 0.7(\text{syst}) \pm 0.6(\text{th})] \times 10^{-8}$, where the systematic uncertainty is the sum in quadrature of 0.5 (acceptance), 0.4 (background subtraction), and 0.2 (normalization) [15]. The 12% theoretical error (th) comes from the effects of varying the shape of the spectrum on the acceptance: we vary w^+ in the ChPT matrix element from -2 to $+2$ and note that the resulting range in acceptance includes that for a pure vector coupling.

In the formalism of ChPT, the above result for $B(K^+ \rightarrow \pi^+ \mu^+ \mu^-)$ implies $w_+ = 1.07 \pm 0.07$ [16]. This can be compared with the values of w_+ extracted from $K^+ \rightarrow \pi^+ e^+ e^-$ described above. We can also compare our result with the prediction of ChPT by using our branching ratio as well as the combined branching ratio and spectral shape fit of Ref. [8]. We find $\Gamma(K^+ \rightarrow \pi^+ \mu^+ \mu^-)/\Gamma(K^+ \rightarrow \pi^+ e^+ e^-) = 0.167 \pm 0.036$, which is about 2.2σ below the ChPT prediction of 0.236 at $w+ = 0.89$. In the range $0.75 < w_+ < 1.13$ ($\pm 1\sigma$), this disagreement varies between 2.7 and 1.8σ. Note that the disagreement with the model of Ref. [6], which predicts $\Gamma(K^+ \rightarrow \pi^+ \mu^+ \mu^-)/\Gamma(K^+ \rightarrow \pi^+ e^+ e^-) = 0.24$, is similar ($\sim 2\sigma$).

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[13] Two samples of $e^\pm$ are used: Dalitz decays of the π^0 from $K^+ \rightarrow \pi^+ \pi^0$ decay are tagged by the 205 MeV/c π^+, and individual tracks making a complete orbit in the central drift chamber are tagged as electrons using orbital time of flight. The π^+ sample is tagged by its $\pi^+ \rightarrow \mu^+ \nu$ decay, observed in the range stack using the TD's.
[14] A trigger hardware problem caused the lower efficiency. The full three-track acceptance shows less variation—detector improvements added a new particle identification tool in this time period that offset the efficiency loss.
[15] There is considerable overlap between the three-track events found in the two analyses. However, these represent a negligible contribution to the full two-track analysis.
[16] We have added the statistical and systematic errors in quadrature for this calculation. The changes in acceptance from $w_+ = 0.89$ to $w_+ = 1.07$ are negligible. We note that $w_+ = -0.61 \pm 0.07$ is also consistent with the value of $B(K^+ \rightarrow \pi^+ \mu^+ \mu^-)$ found here, but we assume that the spectral shape measured by [8] rules out the negative branch.