Upper Limit on the Decay $K^+ \rightarrow e^+ \nu \mu^+ \mu^-$

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(April 13, 2018)

Abstract

An upper limit on the branching ratio for the decay $K^+ \rightarrow e^+ \nu \mu^+ \mu^-$ is set at $5.0 \times 10^{-7}$ at 90% confidence level, consistent with predictions from chiral perturbation theory.
We report here an upper limit on the rare kaon decay \( K^+ \rightarrow e^+\nu\mu^+\mu^- \). This decay together with the related semileptonic decays \( K^+ \rightarrow l^+\nu l'^+ l'^- \), where \( l \) and \( l' \) stand for electron or muon, is of interest for testing the Standard Model in next-to-leading order in the chiral expansion without any further assumptions. For \( K^+ \rightarrow e^+\nu\mu^+\mu^- \) the calculation yields a branching ratio of \( 1.1 \times 10^{-8} \). This decay is a particularly good test of the chiral expansion because the structure dependent terms dominate over the inner bremsstrahlung term due to helicity suppression. The decay \( K^+ \rightarrow e^+\nu\mu^+\mu^- \) has not been seen and no previous limit has been reported, in contrast to the decays \( K^+ \rightarrow e^+\nu e^+ e^- \) and \( K^+ \rightarrow \mu^+\nu e^+ e^- \), which have been observed \[2\] and \( K^+ \rightarrow \mu^+\nu\mu^+\mu^- \) for which an upper limit has been reported \[3\].

The experiment described here used the E787 apparatus \[4\] at the Brookhaven National Laboratory Alternating Gradient Synchrotron. The data were taken between 1989 and 1991. Kaons of 800 MeV/c momentum were tagged by a Čerenkov detector and subsequently stopped in a scintillating fiber target located in the center of the detector (see Fig. 1). Six trigger counters surrounding the target defined the decay volume of the kaons. Charged decay products of the kaon with sufficiently high momentum could leave the target and have their momentum determined in a cylindrical tracking chamber. A range stack of scintillators divided radially into 15 layers and azimuthally into 24 sectors surrounded the tracking chamber. The innermost layer, with a thickness of 0.6 cm, served as trigger counter; the next three layers were 7.6, 5.7 and 3.8 cm thick followed by 11 1.9-cm layers. Phototubes on both ends of the range stack were read out with 500-MHz transient digitizers (TD) \[5\]. A momentum of at least 65 MeV/c was needed for a particle to reach the range stack. Two Pb-scintillator sandwich photon veto systems completed the detector: a “barrel veto” of 14 radiation lengths in the radial direction and two “end cap vetoes” of 12 radiation lengths on the upstream and downstream ends of the detector. The entire apparatus was in a 1-T solenoidal magnetic field. The beam delivered a 1.2-s spill every 3.0 s. Approximately \( 3 \times 10^5 \) kaons stopped in the target per spill, and the dead-time-corrected total exposure was \( 3 \times 10^{11} \) stopped kaons.
The trigger was optimized for the search for $K^+ \rightarrow \pi^+ \mu^+ \mu^−$ \cite{6}. It rejected kaon decays in flight by imposing a delay of at least 1.5 ns between the incident $K^+$ and its decay particles and required two or three charged tracks in the range stack, with none penetrating deeper than 14 cm at 90°. Events with more than 5 MeV in the barrel veto, 10 MeV in the end cap or 5 MeV in the outer regions of the range stack were rejected by the trigger.

The search for $K^+ \rightarrow e^+ \nu \mu^+ \mu^−$ used the same data set and preliminary event selection as Ref. \cite{6}. First it was demanded that three charged tracks, each with momentum less than 172 MeV/c, were found in the drift chamber, pointing back to the kaon stopping region as determined by the target reconstruction software. Photon veto requirements beyond those in the trigger were applied to reject further the copious kaon decays with $\pi^0$s. Good acceptance (80%) for showering electrons was retained by ignoring regions around the charged tracks in these tighter photon vetoes. 14 200 out of $6 \times 10^6$ recorded events passed these requirements.

The major backgrounds at this stage of the analysis were $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ ($K_{e4}$) and $K^+ \rightarrow \pi^0 \mu^+ \nu$ ($K_{\mu3}$) where one of the photons from the $\pi^0$ underwent internal or external conversion in the target to produce the additional two charged tracks in the drift chamber. The $K_{\mu3}$ background was strongly reduced by rejecting events where a pair of oppositely charged drift chamber tracks was found to have a low invariant mass ($m_{ee} < 20 \text{ MeV}/c^2$), assuming electron masses for the particles \cite{7}. The next step of the analysis consisted of using three sets of particle identification methods to separate signal from background. First, a maximum likelihood analysis was performed combining $dE/dx$ information from the drift chamber, $dE/dx$ in the first layer of the range stack, and time of flight from the trigger counter to the range stack. For particles not reaching the range stack the maximum likelihood analysis was replaced by a simple $dE/dx$ cut on the drift chamber information. The likelihood function was normalized using reference data samples and set to identify 90% of the electrons in the momentum region of interest. Second, the negative charged track was required to enter the range stack and the TDs were used to search for a subsequent decay electron. This distinguishes $\mu^−$ from electrons and $\pi^−$ (the latter being predominantly absorbed by a carbon nucleus in scintillator \cite{8}). The efficiency of this electron search was
found to be about 67%. Third, two requirements on kinematic quantities in the range stack were demanded. The masses of the two charged particles in the range stack were calculated from the momentum measured in the tracking chamber and the kinetic energy measured in the range stack and required to be between 60 MeV/c^2 and 150 MeV/c^2. (The r.m.s. resolution on the mass was 10-20 MeV/c^2 for pions and muons.) In order to obtain meaningful masses, it was demanded that the two range stack tracks did not have any counters in common. In addition, it was required that both tracks reached the third layer of the range stack in order to further select muons over pions.

To summarize the particle identification requirements: Tracks entering the range stack had to be consistent with an oppositely charged muon pair hypothesis and the third track, which was not required to enter the range stack, had to have an electron-like particle identification signature.

In the final stage of the analysis the three charged tracks were extrapolated back to the decay vertex, correcting their momenta for energy loss in the target. The missing momentum was assigned to a neutrino, and the invariant mass of the full four-track event was calculated. The signal region was defined by demanding the invariant mass be less than two standard deviations away from the kaon mass (442.3 < m_K < 529.3 MeV/c^2) and the sum of the transverse momenta of the charged particles be larger than 45 MeV/c. K_e4 events are primarily confined to the region below 45 MeV/c. The acceptance of this signal region was 61%, primarily due to the requirement on the transverse momentum. No event was found in the signal region and three were found outside, of which one was very close to the edge of the signal region (see Fig. 2).

The background was estimated to be 0.32 events in the signal region. The main contribution was identified to be K_e4 decays with a particle identification error (0.23 events) and K_e4 decays in which the π^- decayed in flight before reaching the range stack (0.02 events). The background due to K_µ3 was estimated to be 0.07 events.

As a cross check of the background estimate, the requirement that both range stack tracks extend to the third layer was removed. Seven events were found in reasonable agreement
with the expected background of 4.4 events.

A normalization sample of $K^+ \rightarrow \mu^+\nu$ events, taken simultaneously with the data, was used to determine the number of stopped kaons. Data were used to determine accidental losses and the acceptance of the rejection criteria based on timing quantities and particle identification. Monte Carlo simulation using the decay matrix element of Ref. [1] was used to calculate the acceptance of the trigger and the kinematical cuts. The full acceptance was determined to vary between $(1.4 \pm 0.2) \times 10^{-5}$ and $(1.6 \pm 0.3) \times 10^{-5}$ depending on the year in which the data were taken. Table I lists the main acceptance factors for one year (1990).

As a check of the acceptance calculation, the branching ratio for $K^+\pi^-\pi^+$ decay was measured to be $(3.51 \pm 0.57) \times 10^{-5}$ [9]. The world average for this decay is $(3.91 \pm 0.17) \times 10^{-5}$ [10].

Based on zero observed events and a single event sensitivity of $2.2 \times 10^{-7}$, we obtain a 90% confidence level upper limit of $B(K^+ \rightarrow e^+\nu\mu^+\mu^-) < 5.0 \times 10^{-7}$, consistent with the prediction from chiral perturbation theory of $1.1 \times 10^{-8}$ [1].

ACKNOWLEDGMENTS

We gratefully acknowledge the dedicated efforts of the technical staffs supporting this experiment and of the Brookhaven AGS Department. This research was supported in part by the U.S. Department of Energy under contracts DE-AC02-76CH00016, W-7405-ENG-36, and grant DE-FG02-91ER40671 and by the Natural Sciences and Engineering Research Council and the National Research Council of Canada.
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| Acceptance factors |  
|--------------------|---|
| Trigger            | 0.010 |
| Photon veto acceptance and loss due to accidentals | 0.64 |
| 3 tracks in the drift chamber | 0.24 |
| Other reconstruction efficiencies | 0.49 |
| Particle identification | 0.30 |
| Other kinematic cuts | 0.11 |
| Signal region \((442.3 \leq m_K \leq 529.3 \text{ MeV/c}^2 \text{ and } p_T^2 \leq 45^2 \text{ MeV/c})\) | 0.61 |
| Total acceptance   | \(1.6 \times 10^{-5}\) |

**TABLE I.** Acceptance factors used in the search for \(K \rightarrow e^+\nu\mu^+\mu^-\) for 1990 (the other years are comparable). “3 charged tracks in the drift chamber” is the requirement that all three tracks leave the target and are successfully reconstructed in the drift chamber. “Other reconstruction efficiencies” includes full reconstruction in the target and cuts in the beam counters. “Other kinematic cuts” includes the requirements that the tracks in the range stack did not share any counters and reach the third layer.
FIG. 1. Schematic (a) side and (b) end views showing the upper half of the E787 detector.

Č: beam Čerenkov counter, B4: beam hodoscope, I and T: trigger scintillators, RSPC: multiwire proportional chambers.
FIG. 2. Sum of the transverse momentum squared of the three charged particles at the kaon vertex vs. reconstructed kaon mass a) at an earlier stage of the analysis, b) after all rejection criteria have been applied, c) for simulated $K^+ \rightarrow e^+\nu\mu^+\mu^-$ events, and d) for the simulated background of $K^+ \rightarrow \pi^+\pi^- e^+\nu$ and $K^+ \rightarrow \pi^0\mu^+\nu$ at the same stage of the analysis as figure 2a).