Abstract

I give recent results from E791 at BNL with improved upper limits on the branching fractions $B(K^0_L \rightarrow \mu e)$ and $B(K^0_L \rightarrow e e)$ of $8.5 \times 10^{-11}$ and $11.6 \times 10^{-11}$ at 90% C.L. I also give a preliminary result of a new measurement of $B(K^0_L \rightarrow \mu \mu) = 7.6 \pm 0.5 \text{(stat)} \pm 0.4 \text{(syst)} \times 10^{-9}$.

In this report, I describe a search for $K^0_L \rightarrow \mu e$ and $K^0_L \rightarrow e e$ at a sensitivity greater than that previously achieved.\cite{1,2} I also report a new, more precise measurement of the branching fraction for $K^0_L \rightarrow \mu \mu$, made possible by a substantial increase in statistical sensitivity compared to earlier efforts.\cite{3,4}

The decay $K^0_L \rightarrow \mu e$ is forbidden by conservation of the additive quantum numbers associated with electron- and muon-type leptons. Observation of this decay would be the first example of non-conservation of muon- and electron-number and would provide evidence for physics beyond the Standard Model of strong and electroweak interactions. The decays $K^0_L \rightarrow \mu \mu$ and $K^0_L \rightarrow e e$ are permitted in the Standard Model, but are highly suppressed flavor-changing neutral-current decays. An observation of the decay $K^0_L \rightarrow e e$ significantly above Standard Model predictions would be evidence for new physics.

The principal difficulty is achieving the high sensitivity desired while eliminating all backgrounds. These originate mostly from $K^0_L \rightarrow \pi e(\mu)\nu$ decays. One background occurs if the pion decays or is misidentified as a muon. Such events are eliminated by making redundant, precise measurements of each particle’s momentum and requiring that the event be consistent with a two-body decay of a $K^0_L$ originating from the production target. A second background arises if both decay particles are misidentified. Misassignment of particle masses causes some of these decays to be reconstructed with a $\mu e$ or $\mu \mu$ invariant mass at or above the $K^0_L$ mass. Discrimination against these events requires excellent particle identification.

The experiment (E791) was carried out at the B-5 beam line of the BNL AGS with a typical intensity of $4-5 \times 10^{12}$ protons incident per 1.4s spill on 1.4 absorption length Cu target. The neutral beam was produced at 2.75° and had a 65μsr solid angle.

The apparatus is shown in figure 1; it is described more fully in references 1,3,4 and others therein. A drift chamber spectrometer with two sequential analyzing magnets determines the particle identification.
cies momenta and trajectories. It has a resolution characterized by an average $K_L^0 \rightarrow \pi^+\pi^-$ mass resolution of 1.5 MeV/$c^2$. Two planes of $x$-$y$ scintillation hodoscopes (TSC) and lepton identifying detectors follow the spectrometer. Electrons are identified using segmented gas Čerenkov counters and an electromagnetic shower counter array. Time and pulse-height information was recorded for all channels of both systems. The Čerenkov counters have a pion threshold of 8.3 GeV/$c$. The shower counter consists of 13.8 radiation lengths (r.l.) of lead glass, divided between converter blocks (3.3 r.l.) and absorber blocks (10.5 r.l.). Muons are identified with an $x$-$y$ scintillation hodoscope (MHO) downstream of 91 cm of iron. Further identification is provided by a tracking muon rangefinder (MRG) consisting of marble and aluminum absorber plates instrumented at 13 depths with planes of proportional tubes. These are spaced to correspond to 10% momentum intervals. For each event, times in the MHO counters and the state of all MRG tubes were recorded.

Selected events satisfied a hardware trigger in fast electronics and a software trigger in 3081/E processors. The “minimum bias” trigger only required hits in TSC’s and drift chambers and was suitably prescaled. The normalization sample of $K_L^0 \rightarrow \pi^+\pi^-$ events was selected from events passing this trigger. $K_L^0 \rightarrow \mu\mu$ events were selected from those events (without prescale) which also had hits in the MHO indicating that both particles were muons. $K_L^0 \rightarrow ee$ and $K_L^0 \rightarrow \mu e$ events were similarly selected by requiring appropriate signals in the Čerenkov counter or MHO. Each trigger path was independent from all others.

The kinematic analysis done in the 3081/E’s calculated and imposed requirements on the two-body invariant mass ($m_{12}$) and the collinearity angle ($\theta_c$) between the vector from the target to the decay vertex and the measured 2-body momentum vector. Mass solutions for all particle identification combinations consistent with the first level trigger were tested. No restrictions were placed on minimum bias events, which were subsequently fully analyzed offline to monitor the 3081/E selection efficiency. In the analysis, the selection cuts calculated online for the minimum bias sample were applied to $K_L^0 \rightarrow \pi^+\pi^-$ events. The mode dependence was checked and found to be negligible. Events satisfying both trigger levels were written to tape for further analysis.

A pattern recognition algorithm used hits from all chamber planes to identify tracks originating from a common vertex. Precise calculation of each particle’s kinematic quantities were done with two separate fitting algorithms, which also provided measures of the quality of the fit. The two algorithms gave consistent results.

Identification of a particle as an electron required that the trajectory pass close to a single Čerenkov cell, that the time be within 4 ns of that expected time, and that the signals in the lead-glass counters be consistent with those of an electron with that measured momentum. The efficiency of selection criteria for the Čerenkov and lead-glass counters was determined using well identified electrons from $K_L^0 \rightarrow \pi\nu\nu$ decays. The average efficiencies were $0.901 \pm 0.002$ and $0.957 \pm 0.001$ for the two counter systems. Muon candidates were required to have hits in the MHO in spatial and temporal coincidence with a projected particle trajectory within the resolution of the detector and a penetration of the MRG within 3 gaps of that expected. The efficiencies of the selection criteria were determined using muons from $K_L^0 \rightarrow \pi\mu\nu$ decays. They were $0.977 \pm 0.001$ and $0.991 \pm 0.001$ for the MHO and MRG. Sample plots of the response of the lead-glass and MRG to different particle types are shown in figures 2 and 3.

![Figure 2](image-url)  
Figure 2. Plots of energy in the converter versus the top lead glass energy for (a) electrons and (b) pions.

Additional requirements ensured that events were contained within the detector volume and the...
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the kinematic measurements were of high quality. Charged particle momenta were required to be above 1.5 GeV/c to eliminate kinematic regions with very low acceptance. Most events with pion decays and badly scattered particles were eliminated by additional cuts on the quality of the track and vertex fits.

After all cuts, a small sample of lepton-pair events remains. Figure 4 shows \( K_L^0 \rightarrow \mu e \) and \( K_L^0 \rightarrow \mu \mu \) events as scatter plots of \( \theta_c^2 \) versus \( m_{12} \).

One \( K_L^0 \rightarrow e e \) event is contained in a similar plot: it has \( m_{ee} = 488 \text{ MeV}/c^2 \) and \( \theta_c = 0.7 \text{ mrad} \). Only those events in the fiducial region of \( 493 < m_{12} < 505 \text{ MeV}/c^2 \) and \( \theta_c^2 < 2 \text{ mrad}^2 \) satisfied all selection criteria for the processes \( K_L^0 \rightarrow \mu e \) or \( K_L^0 \rightarrow e e \).

The sensitivity was normalized to \( K_L^0 \rightarrow \pi^+\pi^- \) decays chosen from the minimum bias sample. Figure 5 shows the \( \pi \pi \) mass distribution for events with \( \theta_c^2 < 2 \text{ mrad}^2 \), with the distribution for the expected semileptonic background superimposed. The data has been normalized to agree with the data in the region above and below the \( K_L^0 \rightarrow \pi^+\pi^- \) mass peak. The level of the background agrees with the absolute magnitude of the prediction within 5%. After background subtraction and a small correction for the \( K_L^0 \) contamination in the beam, \( N_{\pi\pi} = 16072 \pm 173 \).

Since no \( K_L^0 \rightarrow \mu e \) events are observed, the 90% confidence limit on the branching fraction is given by

\[
B(K_L^0 \rightarrow \mu e) < 2.3 \times \frac{B(K_L^0 \rightarrow \pi^+\pi^-)}{6000 \times N_{\pi\pi}} \times \frac{A_{\pi\pi}}{A_{\mu e}} \times \frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}}.
\]

A similar expression is used to determine a limit on \( B(K_L^0 \rightarrow e e) \). Here \( B(K_L^0 \rightarrow \pi^+\pi^-) = (2.04 \pm 0.04) \times 10^{-3} \) is the \( K_L^0 \rightarrow \pi^+\pi^- \) branching fraction and 6000 is the minimum bias prescale factor. \( A_{\pi\pi} \) and \( A_{\mu e} \) are the acceptances of the detector for \( K_L^0 \rightarrow \pi^+\pi^- \) and \( K_L^0 \rightarrow \mu e \) decays, calculated with a Monte Carlo simulation. The ratios \( A_{\pi\pi}/A_{\mu e} \) and \( A_{\pi\pi}/A_{ee} \) are 1.45 \pm 0.24 and 1.75 \pm 0.30, respectively. The correction factor \( \epsilon_{\pi\pi}, 0.97 \pm 0.015 \), is due to losses from pion interactions, while \( \epsilon_{\mu e} (0.817 \pm 0.016) \) and \( \epsilon_{ee} (0.722 \pm 0.02) \) include the lepton identification and trigger efficiencies quoted above.
and a factor of 0.985 to account for an inefficiency in the lepton pair trigger circuit.

The resulting 90% confidence level upper limit for the branching fraction for $K_L^0 \to \mu e$ is $8.5 \times 10^{-11}$ and for $K_L^0 \to ee$ it is $11.6 \times 10^{-11}$. Based on uncertainties in the normalization and in the relative pion and lepton efficiencies quoted above, we estimate the total systematic uncertainty in the sensitivity to be 6%. Including our earlier result, the limits are $B(K_L^0 \to \mu e) < 6.1 \times 10^{-11}$ and $B(K_L^0 \to ee) < 8.5 \times 10^{-11}$.

The $\mu\mu$ branching fraction is given by

$$B(K_L^0 \to \mu\mu) = \frac{N_{\mu\mu}}{N_{\pi\pi}} \times \frac{A_{\pi\pi}}{A_{\mu\mu}} \times \frac{\epsilon_{\pi\pi}}{\epsilon_{\mu\mu}}.$$  

The factors have definitions similar to those above, with $\epsilon_{\mu\mu} = 0.926$ and $A_{\pi\pi}/A_{\mu\mu} = 1.18$, yielding $B(K_L^0 \to \mu\mu) = (7.6 \pm 0.5 \pm 0.4) \times 10^{-9}$. The errors are statistical and systematic, respectively. This result is preliminary, as some final checks of relative efficiencies and acceptances are being done, but not expected to change significantly.

This result for $B(K_L^0 \to \mu\mu)$ differs by about 2.5 statistical standard deviations from our previous result. Following the analysis reported here, we have again checked the previous analysis, and find no error.

We have now completed the data taking for E791 with an 18 week run in January-May 1990. The detector was improved with a new vacuum decay region window and new upstream-most drift chamber modules, a modified kaon production target, and an improved trigger algorithm. A preliminary analysis of this data yields more than 350 $K_L^0 \to \mu\mu$ events. Figure 6 shows the distribution in the $\mu\mu$ invariant mass for all data sets from E791; the peak contains approximately 750 events. Based on this measure of the sensitivity, we expect a single event sensitivity for $K_L^0 \to \mu e$ to be close to $10^{-11}$ for the full data set from E791.

References


1. New Experimental Limits on $K_L^0 \to \mu e$ and $K_L^0 \to ee$ Branching Ratios, C. Mathiazhagan et al., Phys. Rev. Lett. 63, 2185 (1989).