Search for Lepton-Flavor-Violating Decays of the Neutral Kaon

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The Fermilab KTeV experiment has searched for lepton-flavor-violating decays of the K_L meson in three decay modes. We observe no events in the signal region for any of the modes studied, and we set the following upper limits for their branching ratios at the 90% C.L.: $BR(K_L \to \pi^0\mu^\pm e^\mp) < 7.6 \times 10^{-11}$; $BR(K_L \to \pi^0\pi^0\mu^\pm e^\mp) < 1.7 \times 10^{-10}$; $BR(\pi^0 \to \mu^\pm e^\mp) < 3.6 \times 10^{-10}$. This result represents a factor of 82 improvement in the branching ratio limit for $K_L \to \pi^0\mu^\pm e^\mp$ and is the first reported limit for $K_L \to \pi^0\pi^0\mu^\pm e^\mp$.

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In the standard model of particle physics lepton-flavor-violating (LFV) decays are possible with nonzero neutrino masses and mixing, but the rates for such decays are far beyond the reach of any current experiment [1]. Therefore, the observation of LFV decays would be an indication of new physics. Many scenarios for physics beyond the standard model allow LFV decays. Supersymmetry [2], new massive gauge bosons [1,3], and Technicolor [4] all can lead to LFV decays which might be within reach of current experiments. Searches in K_L decays are complementary to searches in the charged lepton sector, since K_L decays probe the $s \to d\mu e$ transition [1].

In this letter we report on searches for three LFV processes in the KTeV experiment at Fermilab. We present improved limits on the decays $K_L \to \pi^0\mu^\pm e^\mp$ and $\pi^0 \to \mu^\pm e^\mp$ (tagged from $K_L \to \pi^0\pi^0\pi^0$), and we report the first limit on the decay $K_L \to \pi^0\pi^0\mu^\pm e^\mp$.

The KTeV E799-II experiment at Fermilab took data in 1997 and 1999. The combined results from both periods are presented here. Two nearly-parallel K_L beams were produced by 800 GeV/c protons and entered a 65 m long vacuum tank which defined the fiducial volume for K_L decays. Charged particles were detected by two pairs of drift chambers separated by an analysis magnet. Discrimination between charged pions and electrons was provided by a set of transition radiation detectors (TRDs) behind the last drift chamber. Downstream of the TRDs were two planes of trigger hodoscopes, followed by a CsI electromagnetic calorimeter. The calorimeter provided powerful discrimination between electrons and pions based on the transverse shower shape as well as ratio of energy as measured in the calorimeter (E) to momentum as measured in the spectrometer (p), or E/p. The CsI calorimeter had two beam holes to allow the undecayed beam particles to pass through. A beam anti (BA) calorimeter covered the solid angle behind the two beam holes. Photon detectors were positioned around the vacuum decay region, the spectrometer, and the calorimeter to veto particles escaping the fiducial region of the detector.

The muon system was located downstream of the calorimeter, shielded by 10 cm of lead followed by 4 m of steel. Behind the steel was a plane of muon hodoscopes, consisting of scintillator paddles oriented vertically. Behind this hodoscope was another meter of steel, followed by two more planes of scintillator paddles, one oriented vertically and one horizontally. More detail of the KTeV detector can be found in [5].

A detailed Monte Carlo simulation was used to study detector performance and acceptance, to simulate backgrounds, and to select cuts. For the LFV decays, a uniform phase space decay distribution was assumed.

The number of K_L decays in our fiducial volume, which we refer to as the flux, was determined for each decay mode by comparison to a normalization mode with a similar decay topology and a well-known branching fraction. Using a normalization mode similar to the signal mode, keeping selection cuts identical whenever possible, cancels many systematic uncertainties. For the decay $K_L \to \pi^0 \mu^\pm e^\mp$, the normalization mode was $K_L \to \pi^+ \pi^- \pi^0$. For $K_L \to \pi^0 \pi^0 \mu^\pm e^\mp$ and $\pi^0 \to \mu^\pm e^\mp$, the normalization mode was $K_L \to \pi^0 \pi^0 \pi^0_D$, where π^0_D denotes a π^0 Dalitz decay, $\pi^0 \to e^+ e^- \gamma$. The systematic error on the flux was determined by varying the analysis cuts. An additional 2% systematic error due to the efficiency of the muon trigger was included, as well as the uncertainty in the branching fraction of the normalization modes.

We first consider the decay $K_L \to \pi^0 \mu^\pm e^\mp$. The two charged tracks were required to form a good vertex within the fiducial decay volume, with both tracks matching a cluster in the CsI calorimeter. One charged track was required to have $0.95 < E/p < 1.05$ and a transverse shower shape consistent with an electromagnetic shower. A cut on the TRD information (98% efficient for electrons) gave an additional cross-check on electron identification. The second track was required to deposit less than 1 GeV of energy in the calorimeter, consistent with a minimum ionizing muon, and to have a momentum greater than 8 GeV$/c$. The projection of the downstream segment of the muon track was also required to match hits in all three planes of the muon detector, within a road determined by the expected multiple scattering.

The π^0 was reconstructed by its decay to two photons which were detected as electromagnetic clusters in the calorimeter with no associated charged tracks. The energy and position of the neutral clusters and the location of the charged vertex were used to calculate $M_{\gamma\gamma}$, the invariant mass of the two-photon system. $M_{\gamma\gamma}$ was required to be within 1.4σ of the π^0 mass, where σ is the π^0 mass resolution of 1.4 MeV$/c^2$. This requirement was chosen to optimize the significance of a potential signal in the presence of a background linear in $M_{\gamma\gamma}$. Additional background rejection was provided by requiring the square of the π^0 momentum in the K_L rest frame to be positive, since for many backgrounds this quantity had an unphysical negative value.

The flight direction of the parent K_L can be approximated by a line from the center of the target to the decay vertex. We defined p_t to be the sum of the momentum components of all final-state particles perpendicular to this direction. For well-reconstructed signal events p_t^2 should be close to zero. The signal and control regions were defined using a likelihood variable $\boldsymbol{L}$ derived from p_t^2 and the invariant mass of the $\pi^0 \mu e$ system ($M_{\pi^0 \mu e}$) in the following way. The K_L mass distribution from signal Monte Carlo calculations was fit with a Gaussian, and the p_t^2 distribution was fit with a three-component exponential, producing probability density functions (PDFs). These variables were found to be uncorrelated, so the joint PDF was defined as the product of the two single-variable PDFs. Then $\boldsymbol{L}$ was calculated for each event by evaluating the joint PDF at the appropriate p_t^2 and $M_{\pi^0 \mu e}$ values. The signal (control) region was defined by a cut on $\boldsymbol{L}$ chosen to retain 95% (99%) of signal Monte Carlo events after all other cuts were applied. Both the signal and control regions were blind during the analysis. Figure 1 shows the $p_t^2 - M_{\pi^0 \mu e}$ plane with $K_L \to \pi^0 \mu^\pm e^\mp$ signal Monte Carlo events shown as points, and the signal and control regions shown as solid contours.

The dominant background for $K_L \to \pi^0 \mu^\pm e^\mp$ was the decay $K_L \to \pi^\pm e^\mp \nu_e$ (K_{e3}), with a $\pi^\pm$ decay or punch through to the muon hodoscopes, accompanied by two accidental photons faking a π^0. Since accidental photons were often accompanied by other accidental activity, we made stringent antiaccidental cuts to reduce this background. An event was cut if any additional charged tracks were present. We allowed no extra in-time hit pairs in the drift chambers upstream of the analysis magnet and at most two extra in-time pairs downstream of the magnet. We also cut on the number of partial track stubs in the upstream chambers. No more than 300 MeV of energy could be present in any of the photon veto counters surrounding the vacuum decay region, the drift chambers, and the

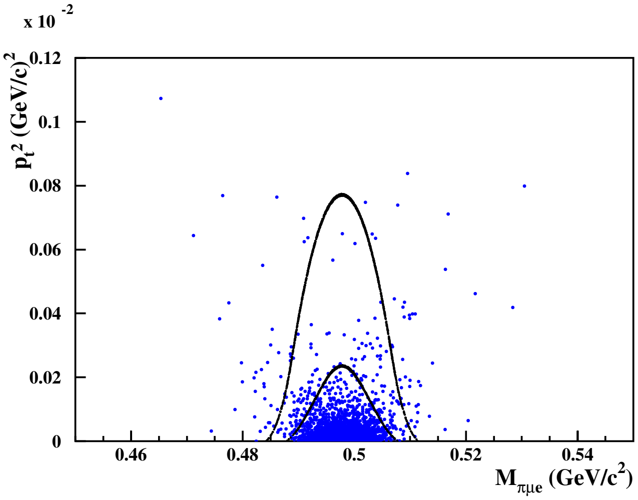

FIG. 1 (color online). Signal Monte Carlo events for the decay $K_L \to \pi^0 \mu^\pm e^\mp$ in the $p_t^2 - M_{\pi^0 \mu e}$ plane. All cuts except the signal region cut have been made. The inner contour shows the signal region, and the outer contour indicates the control region.

calorimeter. The energy deposited in the BA calorimeter was required to be less than 15 GeV.

Figure 2 shows the $M_{\gamma\gamma}$ distribution for data outside the signal and control regions, with all cuts applied except the $M_{\gamma\gamma}$ cut. This distribution shows no evidence of a peak at the π^0 mass. We therefore used the $M_{\gamma\gamma}$ sidebands above and below the π^0 mass region ($0.11\,\mathrm{GeV}/c^2 < M_{\gamma\gamma} < 0.132\,\mathrm{GeV}/c^2$ and $0.138\,\mathrm{GeV}/c^2 < M_{\gamma\gamma} < 0.16\,\mathrm{GeV}/c^2$), but inside the signal or control regions in $\boldsymbol{L}$, to estimate the K_{e3} backgrounds. The resulting K_{e3} background estimate was 0.56 ± 0.23 (2.56 ± 0.40) events in the signal (control) region.

A second source of background was $K_L \to \pi^0 \pi^\pm e^\mp \nu_e$ (K_{e4}), with a charged pion decay or punch through. A kinematic cut to reduce this background was defined by assuming a K_{e4} decay and calculating the magnitude of the unseen neutrino's momentum in the K_L rest frame. For K_{e4} decays, this quantity must be positive, while for signal decays it is usually negative. Requiring this variable to be negative removed most K_{e4} background. The remaining K_{e4} contribution was determined from Monte Carlo simulation to be 0.10 ± 0.05 (1.65 ± 0.20) events in the signal (control) region.

Another possible source of background was $K_L \to \pi^+ \pi^- \pi^0$ decays. These decays could fake the signal if one charged pion decayed to a muon and the second was mistaken for an electron in the calorimeter and TRDs. However, due to the incorrect mass assignments, $M_{\pi^0 \mu e}$ reconstructed about $50\,\mathrm{MeV}/c^2$ below the true K_L mass, with no tail extending near the signal region. The π/e rejection from both the calorimeter and the TRDs suppressed this background to a negligible level. Other sources of background which were considered but found to be negligible included hyperon decays, $K_L \to \pi^\pm \mu^\mp \nu_\mu$ decays, and multiple decays within a single beam bucket. We find an expected total background of 0.66 ± 0.23 (4.21 ± 0.53) events in the signal (control) region.

The signal acceptance for $K_L \to \pi^0 \mu^\pm e^\mp$ was determined from Monte Carlo simulation to be 3.95% (3.91%) for the 1999 (1997) data. The total number of K_L decays in the fiducial region was $(6.17 \pm 0.31) \times 10^{11}$, yielding a single event sensitivity (SES) of $(4.12 \pm 0.21) \times 10^{-11}$ [6].

When we opened the blind regions, we found 0 events in the signal region and 5 events in the control region, consistent with background estimations. Figure 3 shows the $p_t^2 - M_{\pi^0 \mu e}$ plane, with the surviving events shown as solid dots and the signal and control region shown as contours.

The 90% confidence level (C.L.) upper limit was determined for all modes in the following way. We stepped through a range of branching fractions, using a Monte Carlo simulation to produce a Poisson distribution of signal + background events at each branching fraction value. The errors on the SES and backgrounds were taken into account by allowing these quantities to vary as Gaussian distributions with widths equal to their errors. The resulting Poisson distributions were then used to construct confidence bands, using the Feldman-Cousins prescription [7]. From these confidence bands we determined $BR(K_L \to \pi^0 \mu^\pm e^\mp) < 7.6 \times 10^{-11}$ at the 90% C.L. This result represents a factor of 82 improvement over the previous best limit for this mode [8].

We now consider the decay $K_L \to \pi^0 \pi^0 \mu^\pm e^\mp$. The addition of a second π^0 greatly reduces the backgrounds, so we were able to relax some cuts to improve the signal acceptance. Since $K_L \to \pi^0 \pi^+ \pi^-$ is not a background for this mode, we did not make a TRD requirement on the electron track, and there was no cut on the number of partial track stubs. We allowed up to two extra in-time hits in both the upstream and downstream drift chambers and relaxed the $M_{\gamma\gamma}$ cut as described below.

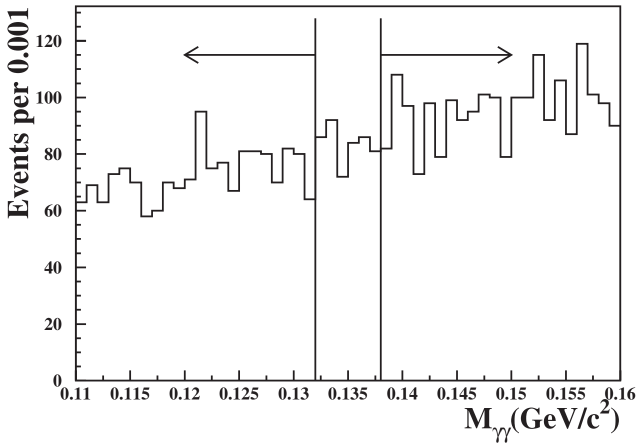

FIG. 2. $M_{\gamma\gamma}$ distribution for $K_L \to \pi^0 \mu^\pm e^\mp$ search data, for events outside the signal and control regions, with all cuts in place except the $M_{\gamma\gamma}$ cut. The arrows indicate the regions used for the sideband background estimate.

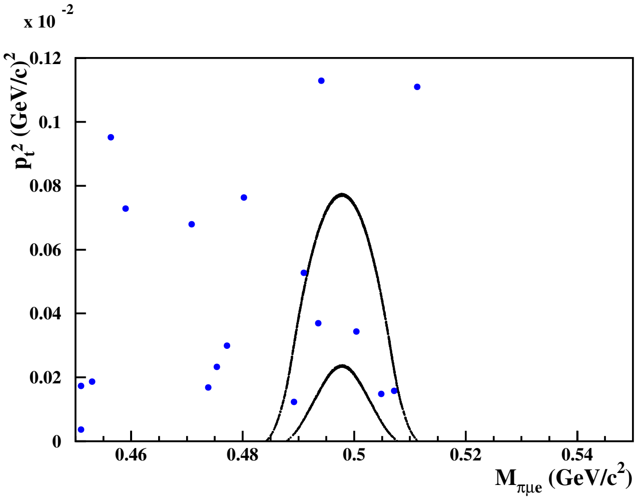

FIG. 3 (color online). Surviving events in the $p_t^2 - M_{\pi^0 \mu e}$ plane for the $K_L \to \pi^0 \mu^\pm e^\mp$ search data. The signal and control regions are shown as the inner and outer solid contours.

Since there are two π^0s in this decay, two neutral vertices can be determined independently of the charged vertex. We required that the distance along the beam direction between the neutral and charged vertices be less than 2.5 m, a cut which retained 95% of the signal events but rejected many backgrounds. In addition, we calculated an average vertex from the neutral and charged vertices, weighting each by their event-by-event position resolutions. Then $M_{\gamma\gamma}$ was calculated using this average vertex and the resulting values were required to be within 3 MeV of the π^0 mass. Additionally, we required the square of the π^0 momentum in the K_L rest frame to be consistent with a signal mode decay.

One important source of background for this mode was the decay $K_L \to \pi^0\pi^0\pi^0_D$. One electron could be mistaken for a muon if it was mismeasured in the calorimeter and if an accidental muon fired the appropriate muon hodoscope paddles. To suppress this background, we made a loose cut on the TRD information for the muon track which rejected 85% of all electrons. This cut effectively eliminated $K_L \to \pi^0\pi^0\pi^0_D$ background.

Other backgrounds arose from K_{e3} or $K_{\mu 3}$ decays with four accidental photons. The $M_{\gamma\gamma}$ sidebands could not be used in this case to estimate the background, since they did not have a smooth distribution. The background estimate was obtained instead by the extrapolation of a linear fit to the log($\boldsymbol{L}$) distribution into the signal and control regions. However, when all cuts were applied, there were not enough events remaining to make a reliable extrapolation. We therefore defined three independent cut sets (kinematic cuts, particle ID cuts, and antiaccidental cuts). When we did not apply cuts from any of the three sets, we had a sufficient number of events to make an extrapolation into the signal region, as shown in Fig. 4. After the extrapolation, we applied the suppression factor for each cut set, as determined from the data. We verified from the data that the three sets were indeed independent, so that we could multiply the three separate suppression factors to get the final background estimate. The total number of background events was thus estimated to be 0.44 ± 0.23 (0.43 ± 0.17) in the signal (control) region. Because of the uncertainties in this procedure, we assigned a systematic error on the background estimate by allowing the fit parameters to vary by 2.5σ from their central values.

The signal acceptance was 2.04% (1.95%) for the 1999 (1997) data set. The total number of K_L decays was $(6.36 \pm 0.24) \times 10^{11}$ yielding a SES for the combined data set of $(7.88 \pm 0.28) \times 10^{-11}$. When the blind regions were opened, we found no events in either the signal or control regions. We set the 90% C.L. limit $BR(K_L \to \pi^0\pi^0\mu^\pm e^\mp) < 1.7 \times 10^{-10}$, the first limit reported for this decay.

The search for $\pi^0 \to \mu^\pm e^\mp$, tagged from $K_L \to \pi^0\pi^0\pi^0$ is identical to the $K_L \to \pi^0\pi^0\mu^\pm e^\mp$ search with the additional requirement that $M_{\mu e}$ be in the π^0 mass region. The background was estimated from both $K_L \to \pi^0\pi^0\pi^0_D$ Monte Carlo simulations and from an extrapolation of the log($\boldsymbol{L}$) distribution into the signal region. The two methods gave consistent results, yielding a background estimate of 0.03 ± 0.015 events in both the signal and control regions. The flux for this mode was determined from (K_L decays) $\times 3 \times BR(K_L \to \pi^0\pi^0\pi^0)$, yielding a SES of $(1.48 \pm 0.059) \times 10^{-10}$. When the blind regions were opened, we found no events in either the signal or control regions. We set the 90% C.L. limit $BR(\pi^0 \to \mu^\pm e^\mp) < 3.6 \times 10^{-10}$. Our limit on $\pi^0 \to \mu^\pm e^\mp$ is equally sensitive to both charge modes, while the previous best limits were not [9,10]. Assuming equal contributions from both charge combinations, our result is about a factor of 2 smaller than the previous best limit on $\pi^0 \to \mu^+ e^-$ and about a factor of 10 smaller than the previous best limit on $\pi^0 \to \mu^- e^+$.

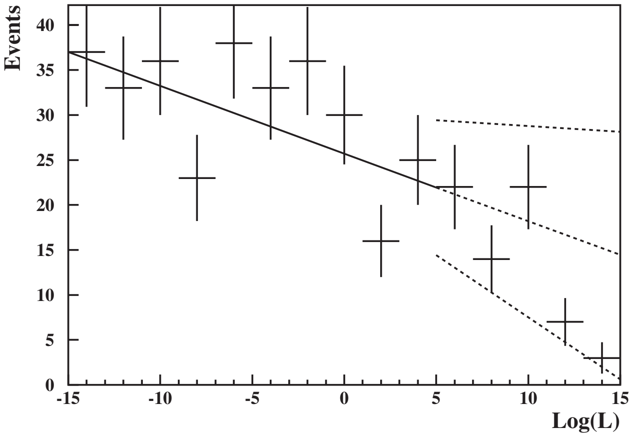

FIG. 4. The log($\boldsymbol{L}$) distribution for $K_L \to \pi^0\pi^0\mu^\pm e^\mp$ search data. The three cuts sets as described in the text have been removed. A linear fit over the region $-15 < \log(\boldsymbol{L}) < 5$ was extrapolated into the signal ($\log(\boldsymbol{L}) > 10$) and control ($5 < \log(\boldsymbol{L}) < 10$) regions to estimate the background. The upper and lower dashed lines indicate the error bands used to assign a systematic error to the background estimate.

Although no evidence for these flavor-violating modes has been found, the pursuit should continue. Given that we find small backgrounds, our techniques could be extended to higher intensity neutral kaon beams.

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[1] L. G. Landsberg, Phys. At. Nucl. **68**, 1190 (2005).

[2] A. Belyaev *et al.*, Eur. Phys. J. C **22**, 715 (2002).

[3] R. N. Cahn and H. Harari, Nucl. Phys. **B176**, 135 (1980).

[4] S. Dimopoulos and J. Ellis, Nucl. Phys. **B182**, 505 (1981); T. Appelquist, N. Christensen, M. Piai, and R. Shrock, Phys. Rev. D **70**, 093010 (2004).

[5] A. Abouzaid *et al.*, Phys. Rev. Lett. **99**, 081803 (2007); A. Alavi-Harati *et al.*, Phys. Rev. D **67**, 012005 (2003); C. Bown *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **369**, 248 (1996).

[6] The single event sensitivity (SES) for the 1997 and 1999 data periods were combined as $SES_{\mathrm{tot}}^{-1} = SES_{99}^{-1} + SES_{97}^{-1}$.

[7] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).

[8] K. Arisaka *et al.*, Phys. Lett. B **432**, 230 (1998).

[9] R. Appel *et al.*, Phys. Rev. Lett. **85**, 2450 (2000).

[10] R. Appel *et al.*, Phys. Rev. Lett. **85**, 2877 (2000).