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% CL: $BR(K_L \to \pi^0\mu^\pm e^\mp) < 7.56 \times 10^{-11}$; $BR(K_L \to \pi^0\pi^0\mu^\pm e^\mp) < 1.64 \times 10^{-10}$; $BR(\pi^0 \to \mu^\pm e^\mp) < 3.59 \times 10^{-10}$. This result represents a factor of 82 improvement in the branching ratio limit for $K_L \to \pi^0\mu e$ 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 non-zero 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. The KTeV beam was produced by 800 GeV/c protons from the Tevatron which were directed onto a BeO target and collimators to create two nearly-parallel K_L beams. The beams entered a 65m long vacuum tank which defined the fiducial volume for accepted decays.

Charged particles were detected by two pairs of drift chambers separated by an analysis magnet that provided a transverse momentum kick of either 0.250 GeV/c (for the 1997 data) or 0.150 GeV/c (for the 1999 data). 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, which had an energy resolution $\sigma(E)/E = 0.45\% \oplus 2\%/\sqrt{E(GeV)}$. The calorimeter provided powerful electron/pion discrimination based on the ratio of energy as measured in the calorimeter (E) to momentum as measured in the spectrometer (p), or E/p. The lateral shower shape in the calorimeter provided additional electron/pion discrimination. 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 4m of steel. Behind the steel was a plane of muon hodoscopes, consisting of 15cm wide 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.

The hardware trigger for this analysis required at least one hit in the last two banks of muon counters and at least three energetic in-time clusters in the CsI calorimeter. The Level 3 software trigger required two tracks which formed a good vertex, with one one track having an E/p value greater than 0.7, consistent with an electron. 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 similar decay with a well-known branching fraction. Using a normalization mode similar to the signal mode 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, $\pi^0 \to e^+e^-\gamma$. For all values of the flux and single event sensitivity quoted below, the systematic error was determined by varying the analysis cuts and noting the change in the measured flux. An additional 2% systematic error on the efficiency of the muon trigger was included, since there was no muon requirement for either normalization mode. The uncertainty in the branching fraction of the normalization modes was included as a systematic error.

We first consider the decay $K_L \to \pi^0\mu^\pm e^\mp$. The signature for this decay was two charged tracks (one electron and one muon) and two neutral clusters. The charged tracks were required to form a good vertex within the fiducial decay volume,and both tracks were required to match a cluster in the CsI calorimeter. One charged track was required to have an E/p ratio within 5% of 1.0 and a transverse shower shape consistent with an electromagnetic shower. A loose 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 hodoscope 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 clusters in the calorimeter with no associated charged tracks and with transverse shower shapes consistent with an electromagnetic shower. The energy and position of the neutral clusters along with 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 1.4 σ of the π^0 mass, where σ is the π^0 mass resolution of 1.4 MeV/c^2, as determined from the normalization mode. This requirement was chosen to optimize the ratio $S/\sqrt{B}$, where S is the number of signal events and B is the number of background events.

The following kinematic cut further reduced backgrounds. Assuming a signal mode decay, we calculated the square of the π^0 momentum in the K_L rest frame. For many backgrounds this quantity has an unphysical negative value. We required this quantity to lie between 0 and 0.025 (GeV/c)^2, where the upper value is the kinematic cutoff in the signal mode.

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 $M_{\pi^0\mu e}$, the invariant mass of the $\pi^0\mu e$ system, in the following way. Using signal Monte Carlo, the K_L mass distribution was fit with a Gaussian, and the p_t^2 distribution was fit with a three-component exponential, producing probability density functions (PDFs) for these variables. Since these variables were found to be uncorrelated, 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 p_t^2 and $M_{\pi^0\mu e}$ value for that event. 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 anti-accidental 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 calorimeter. The energy deposited in the BA calorimeter was required to be less than 15 GeV to veto events in which an energetic photon escaped through one of the beam holes.

Figure 2 shows the $M_{\gamma\gamma}$ distribution for data out-

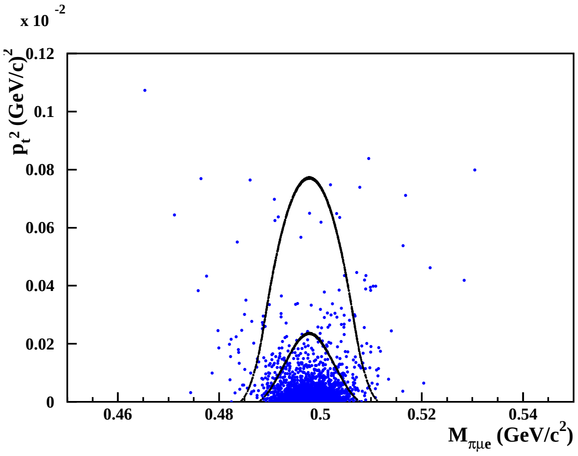

FIG. 1: Signal Monte Carlo events for the decay $K_L \rightarrow \pi^0\mu^\pm e^\mp$ in the $p_t^2 - M_{\pi^0\mu e}$ plane. All cuts except the signal region cut have been made. The inner contour shows the signal region, and the outer contour indicates the control region.

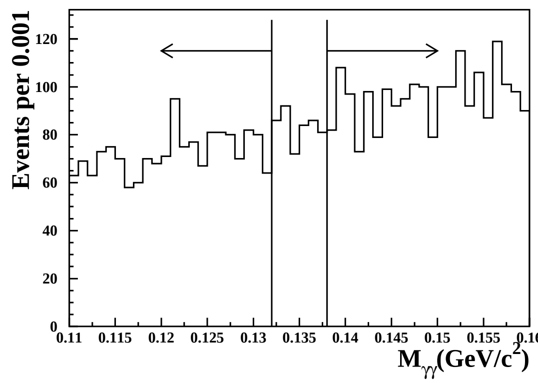

FIG. 2: $M_{\gamma\gamma}$ distribution for $K_L \rightarrow \pi^0\mu^\pm e^\mp$ search data, for events outside the signal and control regions, with all cuts in place except the $M_{\gamma\gamma}$ cut. The arrows show the regions used for the sideband background estimate.

side the signal and control regions, with all cuts applied except the $M_{\gamma\gamma}$ cut. This smooth distribution shows no peak at the π^0 mass. We therefore used the $M_{\gamma\gamma}$ sidebands above and below the π^0 mass region (0.11 GeV/c^2 < $M_{\gamma\gamma}$ <0.132 GeV/c^2 and 0.138 GeV/c^2 < $M_{\gamma\gamma}$ < 0.16 GeV/c^2), but inside the signal or control regions in $\boldsymbol{L}$, to estimate the K_{e3} backgrounds. The K_{e3} background was thus estimated to be 0.56 ±0.23 events in the signal region and 2.56 ±0.49 events in the control region.

A second source of background was $K_L \rightarrow \pi^0\pi^\pm e^\mp \nu_e$ (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 ± 0.050 events in the signal region and 1.65 ± 0.20 events in the control region. Note that the K_{e4} and K_{e3} backgrounds must be added, since K_{e4} decays do not contribute to the K_{e3} sideband background estimate.

Another possible source of background was $K_L \rightarrow \pi^+\pi^-\pi^0$ 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 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 suppress this background to a negligible level, as confirmed by both Monte Carlo simulation and $K_L \rightarrow \pi^+\pi^-\pi^0$ decays in data from a minimum-bias trigger.

Other sources of background were considered but found to be negligible. We find an expected total background of 0.66 ±0.23 events in the signal region and 4.21 ±0.53 events in the control region.

The signal acceptance for $K_L \rightarrow \pi^0\mu^\pm e^\mp$ was determined from Monte Carlo simulation to be 3.95% for the 1999 data and 3.91% for the 1997 data. The total number of K_L decays in the fiducial region was determined from the normalization mode to be $(6.17 \pm 0.31) \times 10^{11}$, and the single event sensitivity (SES) for the combined data set was $(4.12 \pm 0.21) \times 10^{-11}$ [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 $p_t^2 - M_{\pi\mu e}$ plane, with the surviving events shown as solid dots and the signal and control region shown as contours.

The 90% confidence level (CL) upper limit was determined for all modes in the following way. We stepped through a range of possible branching fractions, using a Monte Carlo simulation to produce a Poisson distribution at each 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 $BR(K_L \rightarrow \pi^0\mu^\pm e^\mp) < 7.56 \times 10^{-11}$ at the 90% CL. This result represents a factor of 82 improvement over the previous best limit for this mode. [8]

We now consider the decay $K_L \rightarrow \pi^0\pi^0\mu^\pm e^\mp$. 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 $K_L \rightarrow \pi^0\pi^+\pi^-$ is not a background for this mode, we did not make a TRD requirement on

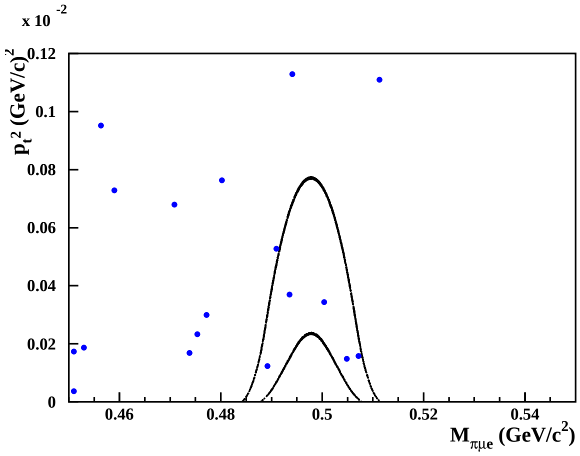

FIG. 3: Surviving events in the $p_t^2 - M_{\pi^0\mu e}$ plane for the $K_L \to \pi^0\mu^\pm e^\mp$ search data. The signal and control regions are shown as the inner and outer solid contours.

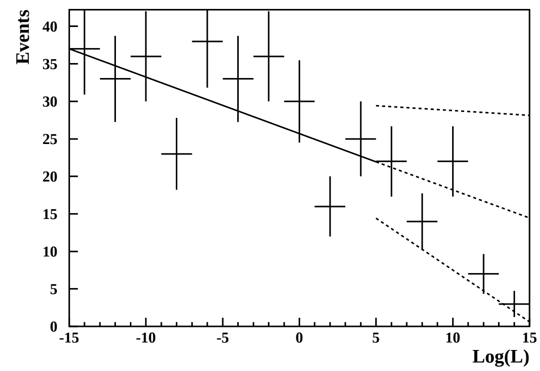

FIG. 4: The log($\boldsymbol{L}$) distribution for $K_L \to \pi^0\pi^0\mu^\pm e^\mp$ search data. The three cuts sets as described in the text have been removed. A linear fit over the region -15<log($\boldsymbol{L}$)<5 was extrapolated into the signal (log($\boldsymbol{L}$)>10) and control (5 <log($\boldsymbol{L}$)< 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.

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.

Since we have two neutral pions in this decay, we can determine a neutral vertex independently of the charged vertex. We required that the difference between the neutral and charged vertices be less than 2.5 meters. In addition, we calculated an average vertex from the neutral and charged vertices, and recalculated $M_{\gamma\gamma}$ using the average vertex. The resulting values were required to lie in the region 0.132 GeV/c^2 $< M_{\gamma\gamma} <$ 0.138 GeV/c^2. Additionally, a kinematic cut on the square of the π^0 momentum in the K_L rest frame was made on both π^0s.

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 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 $K_{\mu3}$ 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 from outside the control region 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 anti-accidental cuts). When we removed all three sets, we had sufficient events to make an extrapolation into the signal region, as shown in figure 4. After the extrapolation, we apply the suppression factor associated with each cut set, as determined from the data. We verified from the data (by applying the cut sets in various combinations) 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 in the signal region and 0.43 ± 0.17 in the control region. Due to the uncertainties in both the extrapolation in log($\boldsymbol{L}$) and the suppression factors, we assign a systematic error on the background estimate by allowing the fit parameters to vary by 2.5 σ from their central values.

The signal acceptance was 2.04% for the 1999 data and 1.95% for the 1997 data. The total number of K_L decays was $(6.36 \pm 0.24) \times 10^{11}$. The SES for the combined data set was $(7.88 \pm 0.28) \times 10^{-11}$. When the blind regions were opened, we found no events in either the signal or control regions. We set the 90% CL limit $BR(K_L \to \pi^0\pi^0\mu^\pm e^\mp) < 1.64 \times 10^{-10}$, which is 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 and from an extrapolation of the log($\boldsymbol{L}$) distribution into the signal region as was done for $K_L \to \pi^0\pi^0\mu^\pm e^\mp$. The two methods gave consistent results, yielding a background estimate of 0.03 $\pm$0.015 events in the signal region and an identical value in the control region. 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% CL limit $BR(\pi^0 \rightarrow \mu^{\pm}e^{\mp}) < 3.59 \times 10^{-10}$. Our limit on $\pi^0 \rightarrow \mu^{\pm}e^{\mp}$ 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 two better than the previous best limit on $\pi^0 \rightarrow \mu^{+}e^{-}$ and about a factor of 10 greater than the previous best limit on $\pi^0 \rightarrow \mu^{-}e^{+}$.

Although no evidence for these flavor-violating modes has been found, the pursuit should not dropped. Given that we find negligible backgrounds, our techniques could clearly be extended to higher intensity neutral kaon beams.

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