First Evidence for the Decay $K_L \to e^+e^-\mu^+\mu^-$

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We present the first evidence for the decay $K_L \to e^+e^-\mu^+\mu^-$ based on the observation of one event with an estimated background of $0.067^{+0.057}_{-0.025}$ event. We determine the branching ratio to be $B(K_L \to e^+e^-\mu^+\mu^-) = (2.9^{+6.7}_{-2.4}) \times 10^{-9}$. In addition, we set a 90% confidence upper limit on the combined branching ratio for the lepton flavor violating decays $K_L \to e^\mp e^\mp \mu^\pm \mu^\pm$ to be $B(K_L \to e^\mp e^\mp \mu^\pm \mu^\pm) < 6.1 \times 10^{-9}$ assuming a uniform phase space distribution. [S0031-9007(96)00301-8]

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We present the first evidence for the decay $K_L \to e^+e^-\mu^+\mu^-$. This decay is expected to proceed primarily via a two-photon intermediate state $K_L \to \gamma^*\gamma^* \to e^+e^-\mu^+\mu^-$ [1–4]. Because one of the virtual photons must have an invariant mass greater than $2m_\mu$, the decay is sensitive to the structure of the $K_L\gamma^*\gamma^*$ form factor. This form factor must be known accurately in order to extract the contribution of second-order weak processes to the decay $K_L \to \mu^+\mu^-$, which is sensitive to the Cabibbo-Kobayashi-Maskawa element V_{td} [5–10]. Predictions for the $K_L \to e^+e^-\mu^+\mu^-$ branching ratio are 8.0×10^{-10} for a calculation based on a constant form factor [1] and 2.3×10^{-9} for a calculation based on the vector meson dominance model [2]. The previous experimental 90% confidence upper limit on the branching ratio is 4.9×10^{-6} [11].

This measurement was carried out as part of the Fermilab experiment E799 which has previously reported precision measurements of the related processes $K_L \to \gamma\gamma^* \to \mu^+\mu^-\gamma$ [12] and $K_L \to \gamma^*\gamma^* \to e^+e^-e^+e^-$ [13]. A detailed description of the E799 detector can be found elsewhere [14]. Two K_L beams were produced by 800 GeV protons striking a Be target. A 70 m long vacuum decay volume began 90 m downstream of the target. Decay products of the K_L's were detected by a spectrometer located downstream of the decay volume. The mean energy of the kaons whose decays were accepted by the trigger described below was about 80 GeV. The spectrometer included four drift chambers and a magnet for analyzing the momentum and trajectories of charged particles. The momentum resolution is given by $(\sigma_p/p)^2 = (5 \times 10^{-3})^2 + \{1.4 \times 10^{-4}(p[\mathrm{GeV}/c])\}^2$. A lead glass calorimeter was used to measure the energies and positions of electrons and photons. The average energy resolution for accepted electrons was 4.4%. Two beam holes were symmetrically located above and below the center of the lead glass array. Seven planes of veto counters at various locations in the detector were used to detect decay products outside the chamber and calorimeter acceptances. Two scintillator hodoscopes, used to trigger on charged particles, were located before the calorimeter. Downstream of the calorimeter was a lead wall 0.73 interaction length thick. A scintillation counter hodoscope located just downstream of the lead wall was used to veto events with showers from charged pions hadronically interacting in the lead glass or lead wall. Finally, a muon trigger plane consisting of 16 vertically oriented, nonoverlapping scintillation counters was located just downstream of a 3 m steel muon filter.

The trigger for the $K_L \rightarrow e^+e^-\mu^+\mu^-$ events required at least two hits in each of the two trigger hodoscopes, in each of the drift chamber planes, and in nonadjacent counters in the muon trigger plane, and at least 6 GeV of energy deposit in the calorimeter. In addition, the veto counters were used to reject events with charged particles escaping the detector fiducial region. Events were also rejected if the total energy deposit in the hadron veto hodoscope located behind the lead wall was greater than that equivalent to three traversing minimum ionizing particles.

Candidate $K_L \rightarrow e^+e^-\mu^+\mu^-$ events were required to have two positively and two negatively charged tracks. The four charged particles were required to be consistent with two electrons and two muons, where electrons were identified by $0.8 < E/p < 1.2$, and muons were identified by $E < 3$ GeV and $p > 7$ GeV$/c$ where p is the track momentum and E is the energy of the calorimeter cluster associated with the track. Both the electron and muon pairs were required to consist of opposite sign tracks. At most, one of the four particles was allowed to pass through one of the lead glass beam holes. In this case, no identification based on the shower energy of the particle could be made for this track. The reconstructed decay vertex was required to be within the fiducial decay volume. A track separation cut required that tracks not share hits in both the horizontal and vertical views of the most upstream drift chamber in order to reject events in which a photon converted in the vacuum window immediately upstream of this chamber.

In Fig. 1, we show the P_t^2 vs $M_{ee\mu\mu}$ distribution of Monte Carlo $K_L \rightarrow e^+e^-\mu^+\mu^-$ events that passed the above (first stage) cuts, where $M_{ee\mu\mu}$ is the reconstructed invariant mass and P_t is the component of the reconstructed K_L momentum perpendicular to a vector pointing from the production target to the reconstructed decay vertex. The Monte Carlo generator included radiative corrections [15] with a low energy photon cutoff of 0.25 MeV in the K_L center of mass. Radiative effects account for the scatter of events at large P_t^2 and low $M_{ee\mu\mu}$. We define the signal region for $K_L \rightarrow e^+e^-\mu^+\mu^-$ to be $P_t^2 < 5.0 \times 10^{-4}$ (GeV$/c$)^2, and $0.475 < M_{ee\mu\mu} < 0.515$ GeV$/c^2$. The signal region acceptance is 94.2% for the Monte Carlo $K_L \rightarrow e^+e^-\mu^+\mu^-$ events that passed the first stage cuts. We show the corresponding distribution for the data in Fig. 2.

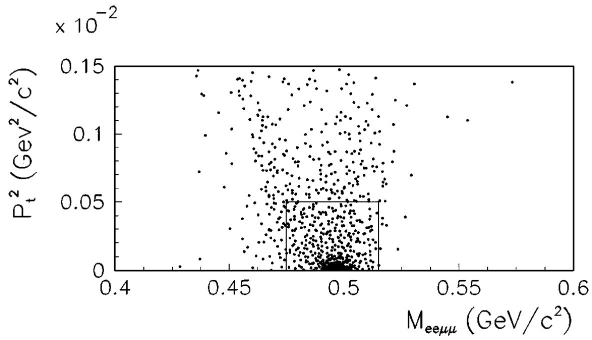

FIG. 1. The P_t^2 vs $M_{ee\mu\mu}$ distribution for the Monte Carlo $K_L \rightarrow e^+e^-\mu^+\mu^-$ events after the first stage cuts described in the text. The Monte Carlo generator included radiative corrections with a low energy photon cutoff of 0.25 MeV in the K_L center of mass. The box is the signal region.

In searching for rare events, it is important to carefully choose cuts in an unbiased fashion. In this analysis, we blanked out the signal region and selected cuts to reject events outside of the signal region as described below. Once the signal region was examined, no further changes to the cuts were made. The events in Fig. 2 with $M_{ee\mu\mu} < 0.500$ GeV$/c^2$ are predominantly $K_L \rightarrow \pi^+\pi^-\pi^0$ decays with the π^0 undergoing Dalitz decay, $K_L \rightarrow \pi^+\pi^-\pi^0_D$ where π^0_D represents $\pi^0 \rightarrow e^+e^-\gamma$, and in which both charged pions were misidentified as muons due to decay in flight or accidental activity in the muon counters. These events were reduced by requiring that there be no extra clusters in the calorimeter that were not associated with the charged tracks. In addition, to reduce events with a pion decay in flight, the position difference between the upstream and downstream track segments at the midplane of the magnet for muon candidate tracks was required to be less than 2 mm in the horizontal view (magnet matching cut). This cut rejected those events with tracks for which the momentum was poorly determined and which could, therefore, have a large error in the determined invariant mass. The events in Fig. 2 with $M_{ee\mu\mu} > 0.500$ GeV$/c^2$ are predominantly events with two decays consisting of combinations of $K_L \rightarrow \pi e \nu$ and $K_L \rightarrow \pi \mu \nu$ occurring within the same $\approx$2 ns beam RF bucket and for which

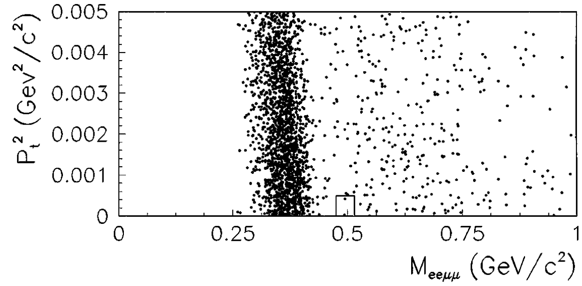

FIG. 2. The P_t^2 vs $M_{ee\mu\mu}$ distribution for candidate $K_L \rightarrow e^+e^-\mu^+\mu^-$ decays after the first stage cuts. The box is the signal region.

the pions were misidentified. These events were largely rejected by requiring that the χ^2 of the fitted decay vertex reconstructed by extrapolation of the four tracks be less than 50 for 5 degrees of freedom. This cut accepted 90.6% of the Monte Carlo $K_L \to e^+e^-\mu^+\mu^-$ events.

The background due to events with two simultaneous K_{l3} decays was estimated as follows. Since these events have a fairly flat χ^2 distribution for the vertex reconstruction, they were selected from the events that passed the first stage cuts by requiring $\chi^2 > 500$. Of these, two events fall within the signal mass range. Requiring $M_{ee\mu\mu} > 0.500$ GeV$/c^2$ removes $K_L \to \pi^+\pi^-\pi^0_D$ events and yields a clean sample of events with two simultaneous K_{l3} decays. Of these events, 10% fall within the P_t^2 signal range. Finally, an extrapolation of a linear fit to the χ^2 distribution indicates that 3.8% would satisfy the $\chi^2 < 50$ cut. This background is then estimated as 2 events $\times$ 0.10 $\times$ 0.038 $= 0.008^{+0.010}_{-0.005}$ event.

In order to estimate the background from $K_L \to \pi^+\pi^-\pi^0_D$, we extrapolated the data into the signal region using an exponential fit to the data in the range $0.385 < M_{ee\mu\mu} < 0.475$ GeV$/c^2$. In order to enhance the statistical accuracy of the fit, we removed the magnet matching, the muon cluster energy, and the muon momentum cuts which increased the number of events by a factor of 2.0. The exponential fit to the data is shown in Fig. 3. For comparison, Monte Carlo $K_L \to \pi^+\pi^-\pi^0_D$ events are also shown. The fitted exponential slopes are -72.4 ± 14.5 (GeV$/c^2)^{-1}$ for the data and -68.0 ± 2.8 (GeV$/c^2)^{-1}$ for the Monte Carlo events. Extrapolating the fit for the data into the signal region and taking into account the factor of 2 rejection from the combined magnet matching, muon momentum, and muon cluster energy cuts, the background is estimated to be $0.021^{+0.043}_{-0.015}$ event.

Another source of background is from radiative K_{e3} with internal photon conversion $K_L \to \pi^\pm e^\mp \nu(\gamma \to ee)$ and from $K_L \to \pi^\pm e^\mp \nu \pi^0_D$ with the charged pion and one of the electrons misidentified as muons. A sample of these events can be selected by choosing events with like-sign ee and $\mu\mu$ pairs after applying the first stage cuts and the $\chi^2 < 50$ cut. There are 10 of these events. Of these 10 events, 2 are in the P_t^2 signal range, 3 are in the $M_{ee\mu\mu}$ signal range, 2 pass the extra cluster cut, and 1 passes the combined magnet matching, muon momentum, and muon shower energy cuts. We expect twice as many unlike sign pair events due to combinatorics. This background is then estimated as $10 \times 0.2 \times 0.3 \times 0.2 \times 0.1 \times 2 = 0.024^{+0.052}_{-0.020}$ event.

We also considered background from $K_L \to \mu^+\mu^-\gamma$ decays [12] with conversion of the photon in the vacuum window. The number of events expected is 1.4 without the track separation cut. The track separation cut based on hit sharing in the most upstream drift chamber reduced this background to 0.014 ± 0.004 events while accepting 85% of Monte Carlo $K_L \to e^+e^-\mu^+\mu^-$ events. Possible background from the hyperon decay $\Xi^0 \to \Lambda\pi^0_D \to p\pi^-e^+e^-\gamma$ could be completely rejected by requiring that the reconstructed energy be less than 200 GeV due to the short proper lifetime of the hyperon.

After all the cuts, the 216 events shown in Fig. 4 remain. One event is left in the signal region with an expected combined background of $0.067^{+0.057}_{-0.025}$ event. For this event, the particle associated with the μ^- passed through one of the beam holes in the lead glass. This track projects onto one of the hit muon trigger counters. The $ee\mu\mu$, ee and $\mu\mu$ invariant masses for this event are 0.494, 0.103, and 0.300 GeV$/c^2$, respectively. These along with the value of P_t^2 for this event are compared with Monte Carlo distributions in Fig. 5 where the Monte Carlo decays were generated using a constant $K_L\gamma^*\gamma^*$ form factor. The probability of a Monte Carlo event having an ee invariant mass or a $\mu\mu$ invariant mass greater than that of the observed event are 8% and 25%, respectively. If the particle that passed through the beam hole is assigned the electron mass and the other identified muon is assigned the pion mass, the resulting πeee invariant mass is 0.543 GeV$/c^2$. The probability of this event being either $K_L \to \pi e\nu(\gamma \to ee)$ or $K_L \to \pi e\nu\pi^0_D$ is, therefore, extremely small. Similarly, if both identified muons are assigned the pion mass, the resulting $\pi\pi ee$ mass is 0.576 GeV$/c^2$ so that the probability

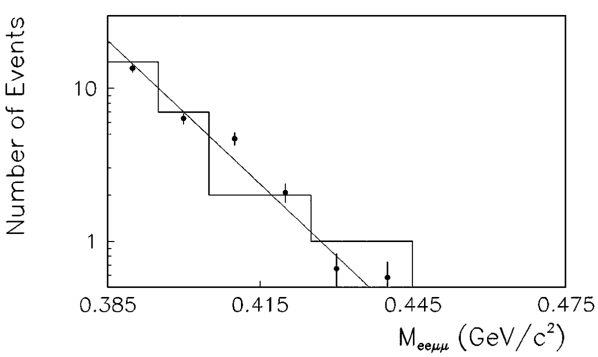

FIG. 3. The $M_{ee\mu\mu}$ distributions for $0.385 < M_{ee\mu\mu} < 0.475$ MeV$/c^2$. The histogram is the data. The points are the $K_L \to \pi^+\pi^-\pi^0_D$ Monte Carlo events. The exponential fit to the data is shown.

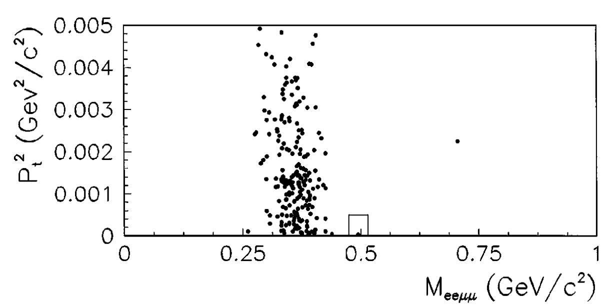

FIG. 4. The P_t^2 vs $M_{ee\mu\mu}$ distribution for candidate $K_L \to e^+e^-\mu^+\mu^-$ decays after all of the analysis cuts. The box is the signal region.

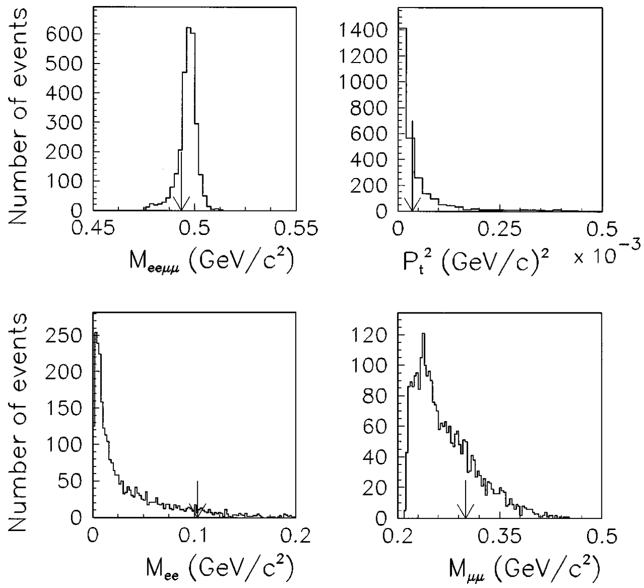

FIG. 5. The distributions of $M_{ee\mu\mu}$, P_t^2, M_{ee}, and $M_{\mu\mu}$ for accepted Monte Carlo $K_L \rightarrow e^+e^-\mu^+\mu^-$ events, where the arrows indicate the locations of the observed event.

of the event being $K_L \rightarrow \pi^+\pi^-\pi^0_D$ is also extremely small. The probability of $K_L \rightarrow \mu^+\mu^-\gamma$ with photon conversion in the vacuum window having an ee mass greater than that of the observed event is 0.2%.

The four-track decay mode $K_L \rightarrow \pi^+\pi^-\pi^0_D$ was used for normalization. The trigger was the same as for the signal mode except that there were no requirements on either the muon trigger or hadron veto hodoscopes. Monte Carlo simulations based on input from muon calibration runs as well as minimum bias trigger data were used to determine the efficiency of the muon trigger hodoscope requirement for those $K_L \rightarrow e^+e^-\mu^+\mu^-$ decays that satisfied the other trigger requirements. Similar Monte Carlo studies that included event-by-event overlay of measured beam-related accidental activity showed that $(44 \pm 4)\%$ of $K_L \rightarrow e^+e^-\mu^+\mu^-$ decays were lost due to the hadron veto counter requirement [16].

Since both the signal and the normalization modes consisted of four-track events, uncertainties due to tracking tended to cancel in the ratio of their acceptances. Cuts similar to those used in the signal mode were applied. In addition, one extra cluster in the calorimeter not associated with a charged track was required due to the photon in the $\pi^0 \rightarrow ee\gamma$ decay and $M_{e^+e^-\gamma}$ was required to be in the range of 0.120 and 0.150 GeV/c^2. Monte Carlo study showed that 1.3% of the reconstructed $K_L \rightarrow \pi^+\pi^-\pi^0_D$ decays are from $K_L \rightarrow \pi^+\pi^-\pi^0$ with external photon conversion. Other backgrounds were negligible.

We have observed one $K_L \rightarrow e^+e^-\mu^+\mu^-$ candidate event with an estimated background of $0.067^{+0.057}_{-0.025}$ events. A 0.067 event background has about a 7% probability of yielding one or more observed events. Based on the number of accepted $K_L \rightarrow \pi^+\pi^-\pi^0_D$ decays (233 $\pm$ 15), the $K_L \rightarrow \pi^+\pi^-\pi^0_D$ acceptance of $(1.78 \pm 0.05)\%$ with prescale factor of 3600, the $K_L \rightarrow e^+e^-\mu^+\mu^-$ acceptance of $(1.1 \pm 0.1)\%$, and the one candidate $K_L \rightarrow e^+e^-\mu^+\mu^-$ decay, the branching ratio of $K_L \rightarrow e^+e^-\mu^+\mu^-$ is calculated to be $B(K_L \rightarrow e^+e^-\mu^+\mu^-) = (2.9^{+6.7}_{-2.4}) \times 10^{-9}$. This is consistent with both the vector meson dominance model and the constant form factor predictions.

In addition, we searched for the lepton number violating decays $K_L \rightarrow e^{\mp}e^{\mp}\mu^{\pm}\mu^{\pm}$ by removing the requirement that the electron and muon pairs consist of opposite sign leptons. Assuming that the final state particles are uniformly distributed in phase space, the acceptance for these events is $(1.2 \pm 0.1)\%$. No events were seen, leading to a 90% confidence level upper limit of 6.1×10^{-9} on the combined $K_L \rightarrow e^{\mp}e^{\mp}\mu^{\pm}\mu^{\pm}$ branching ratio.

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