Limit on the Branching Ratio of $K_L \to \pi^0 e^+ e^-$

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We report the results of a search for the decay $K_L \to \pi^0 e^+ e^-$ conducted by E799 at Fermilab. The largest contribution to this decay mode is expected to be CP violating. Observations of this decay could either confirm the standard model mechanisms for CP violation or point to physics beyond the standard model. No such events were seen in our search. The 90% confidence level upper limit is determined to be $B(K_L \to \pi^0 e^+ e^-) < 4.3 \times 10^{-9}$.

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The decay $K_L \to \pi^0 e^+ e^-$ has recently generated considerable interest because of its potential for shedding light on the mechanisms that cause CP violation and for discovering non-standard-model processes. The dominant contribution to this mode is expected to be CP violating, as described in the previous article [1]. Branching ratio predictions in the standard model are at the 10^{-11}–10^{-12} level [2,3]; exotic processes can enhance this level [4,5]. As experimental limits are still far from the standard model predictions, there is much room for unexpected contributions to be discovered. Searching for such rare processes poses experimental challenges because of the many possible backgrounds from other decay modes of the K_L. Most recently the background due to the radiative K_L decay $K_L \to e^+ e^- \gamma\gamma$ has been considered as a serious concern at the 10^{-11} level [6]. The best experimental limits thus far on the branching ratio of $K_L \to \pi^0 e^+ e^-$ are 5.5×10^{-9} [7] and 7.5×10^{-9} [8] at the 90% confidence level, where the limit in Ref. [8] was obtained by a previous generation of this experiment, E731 at Fermilab. We report here the results from a more sensitive search.

Experiment E799 at Fermilab was a dedicated, rare K_L decay search. Two K_L beams were produced by interactions of 800 GeV protons from the Fermilab Tevatron in a beryllium target. A description of the experiment and detector can be found in the preceding paper [1] and in other publications [9]. Only the most critical elements will be discussed here. The K_L decays were reconstructed using a spectrometer with a track momentum resolution of $(\sigma_p/p)^2 = (5 \times 10^{-3})^2 + (1.4 \times 10^{-4}(p[\mathrm{GeV}/c]))^2$ and a lead-glass electromagnetic calorimeter with an electron energy resolution, σ_E/E, of about 4.4%. The π^0 mass resolution measured in $K_L \to \pi^+\pi^-\pi^0$ decays was about $6.0\,\mathrm{MeV}/c^2$. Because of the good track momentum resolution and photon energy resolution, kinematic cuts were extremely powerful in eliminating background.

The trigger for this decay mode was designed to ac-

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cept events with two electrons and at least two photons in the lead-glass, and has been described elsewhere [9]. The most important elements of the trigger were requirements of four in-time clusters of energy in the lead-glass (see Ref. [1]), a minimum lead-glass energy deposition of 55 GeV, and hits in the drift chambers consistent with the passage of two charged particles. To measure the K_L flux at the detector, a prescaled "Dalitz" trigger designed to accept the decays $K_L \to e^+e^-\gamma$ (K_L Dalitz decay) and $K_L \to \pi^0\pi^0$ followed by a $\pi^0 \to e^+e^-\gamma$ decay ($K_L \to \pi^0\pi^0_D$) was taken. This trigger had almost identical track requirements but required three or five clusters in the lead-glass and a minimum lead-glass energy deposition of 6 GeV.

Events were first selected by requiring two tracks which originated from a common vertex in the fiducial decay volume of the detector and which pointed to electromagnetic clusters in the calorimeter. Electrons were selected by requiring the cluster energy associated with each track to match the track momentum to within 15%. Exactly two extra electromagnetic clusters not associated with tracks were required as photon candidates. The two-photon invariant mass ($M_{\gamma\gamma}$) was calculated assuming the photons originated from the track vertex and was required to be within 14 MeV/c^2 of the π^0 mass (a 2.5σ cut). After this cut was made the two-photon energies were scaled as a function of their respective energy resolutions such that $M_{\gamma\gamma}$ was constrained to the nominal π^0 mass. These scaled energies were then used when the total invariant mass ($M_{\pi ee}$) and momentum transverse to the initial K_L direction (P_t) were calculated.

Fiducial and kinematic cuts were made to ensure that the events were well understood. Events with tracks or clusters within 6 mm of either lead-glass beam hole were rejected. Cuts on the self-consistency of each track and the quality of the vertex between them were made. To reduce contamination from hadrons which may shower in the lead-glass, a cut was made requiring the transverse profile of all clusters to be consistent with that of electromagnetic showers. A cut was also made to remove events with extra photons below the cluster trigger threshold.

To search for a decay at the 10^{-9} level, the experiment used high intensity beams which enhanced not only the K_L flux but also the flux of other neutral particles, most importantly, neutrons. The preceding paper [1] describes the activity and possible backgrounds that arise in the detector due to neutrons. Primarily they cause backgrounds by hitting the lead-glass and creating a shower, which is then misidentified as a photon. This accidental energy enhances several backgrounds to the decay $K_L \to \pi^0e^+e^-$. To understand the effects of this activity on both signal and background acceptance, a special trigger was used to select "accidental events" [1], and these events were embedded in Monte Carlo–generated events.

The most important backgrounds to the decay $K_L \to \pi^0e^+e^-$ arise from the following K_L decays: $K_L \to \pi^0\pi^0$ followed by $\pi^0 \to e^+e^-\gamma$ ($K_L \to \pi^0\pi^0_D$), $K_L \to \pi^+\pi^-\pi^0$, $K_L \to e^+e^-\gamma$, and $K_L \to \pi^\pm e^\mp\nu_e(\overline{\nu_e})$ (K_{e3}). The first three backgrounds are easily removed by simple kinematic cuts. To remove the $\pi^0\pi^0_D$ decays the invariant e^+e^- mass (M_{ee}) was required to be above 115 MeV/c^2. Since the decay $\pi^0 \to e^+e^-\gamma$ is a Dalitz decay the M_{ee} spectrum is steeply falling. Any significant background due to this decay is removed by the M_{ee} cut. To remove $K_L \to \pi^+\pi^-\pi^0$ decays, events whose reconstructed $\pi^+\pi^-\pi^0$ mass was within 60 MeV/c^2 of the K_L mass were rejected. Backgrounds from the decay $K_L \to e^+e^-\gamma$ arose primarily from the additional bremsstrahlung photons (Ref. [6]). To remove this type of event, a cut was made on the minimum separation between the extrapolation of a track segment upstream of the magnet to the lead-glass and the photon position at the glass. This minimum track-cluster separation was required to be greater than one lead-glass block width, or 5.8 cm. After these three cuts were made the loss in $K_L \to \pi^0e^+e^-$ acceptance was 15%.

Because of the high accidental activity in the detector, K_{e3} decays contributed significantly more background to this search than to previous searches, and a new strategy for removing them was necessary. The K_{e3} decay contributed backgrounds to this search in two ways. The first contribution was due to a K_{e3} decay in coincidence with both a bremsstrahlung photon and an accidental photon cluster. The second occurred when there were two accidental photon clusters in coincidence with a K_{e3} decay. The first contribution was removed by the cut on the track-cluster separation described above. To cut out events with two accidental photons, the analysis took advantage of the fact that accidental photons tend to be low in energy and near the beam holes of the lead-glass, and thus do not contribute much transverse momentum to the decay. Therefore, in order for a K_{e3} decay to pass the transverse momentum cut, the πe pair has to have low transverse momentum as well; in other words, the πe pair contains most of the parent K_L energy. As a result, the pion and electron are emitted preferentially back to back in the K_L rest frame. This configuration implies a very specific relation among the angles between a photon in the decay and each charged particle. For each photon we define a quantity $\Sigma^i_{\cos}$:

$$\Sigma^i_{\cos} \equiv \cos\alpha^i + \cos\beta^i, \tag{1}$$

where α^i and β^i are the angles between the ith photon and each electron candidate in the center-of-mass frame of that photon and the two electron candidates. For K_{e3} decays where the electron and pion are back to back $\Sigma^i_{\cos}$ is near 0. For decays where the tracks have a small opening angle, i.e., Dalitz decays, $\Sigma^i_{\cos}$ is near -2. To remove backgrounds where both $\Sigma^i_{\cos}$'s are small the product $\Sigma^1_{\cos} \times \Sigma^2_{\cos}$ is required to be above 0.05. This cut decreases the $K_L \to \pi^0e^+e^-$ acceptance by 15% while removing 35% of the remaining K_{e3} background.

Figure 1 shows $\Sigma^1_{\cos} \times \Sigma^2_{\cos}$ for all events passing a loose (100 MeV/c^2) K_L invariant mass cut and after the cut

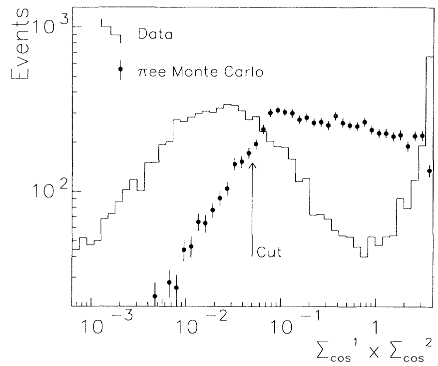

FIG. 1. The product of the sums of the cosines distributions for both the $\pi^0 e^+e^-$ candidates and the $K_L \to \pi^0 e^+e^-$ Monte Carlo simulation. The lower hump is due to K_{e3} events and the peak at 4 is from $K_L \to \pi^0\pi^0_D$ events.

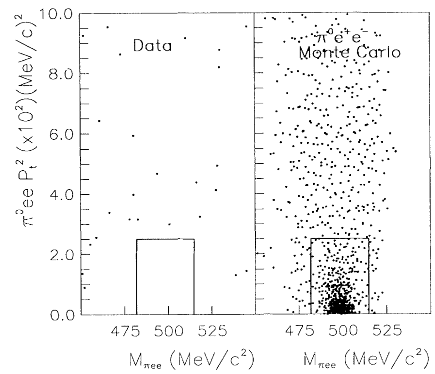

FIG. 2. The invariant mass versus the P_t^2 for the signal and the $K_L \to \pi^0 e^+e^-$ candidates in both the data and the Monte Carlo simulation, after all other cuts were made.

on the invariant $\pi^+\pi^-\pi^0$ mass was made, for both the data and the Monte Carlo simulation. The Monte Carlo simulation was generated with a phase space distribution. The peak in the data at $\Sigma^1_{\cos} \times \Sigma^2_{\cos} = 4$ signals the presence of $K_L \to \pi^0\pi^0_D$ events, which are removed by the cut on M_{ee}. The K_{e3} decays, which dominate the data, have a low $\Sigma^1_{\cos} \times \Sigma^2_{\cos}$, while the $K_L \to \pi^0 e^+e^-$ decays populate a broader region of the allowed range.

Finally, the reconstructed $\pi^0 e^+e^-$ mass was required to be within $16.5\,\mathrm{MeV}/c^2$ of the K_L mass (a 3σ cut) and the P_t^2 was required to be less than 250 $(\mathrm{MeV}/c)^2$ (a 90% efficient cut). Figure 2 shows the resulting P_t^2 vs $M_{\pi ee}$ distributions for both data and $K_L \to \pi^0 e^+e^-$ Monte Carlo simulation. The remaining events in the data are consistent with K_{e3} decays with accidental photons. After comparison of Fig. 2 with Fig. 1 of [1] it is clear that the K_{e3} decay contributed a larger background to the $K_L \to \pi^0 e^+e^-$ search than did the $K_{\mu 3}$ decay to the $K_L \to \pi^0\mu^+\mu^-$ search. This occurred because the $\pi^\pm\mu^\pm$ rejection in this experiment was over twice as good as the $\pi^\pm e^\pm$ rejection. To predict the number of K_{e3} decays in the region shown in Fig. 2 and in the final signal box, the K_{e3} Monte Carlo simulation was normalized to the kinematic region $1000\,(\mathrm{MeV}/c)^2 < P_t^2 < 5000\,(\mathrm{MeV}/c)^2$ and $450\,\mathrm{MeV}/c^2 < M_{\pi ee} < 550\,\mathrm{MeV}/c^2$. The K_{e3} Monte Carlo simulation predicts 28.5 ± 2.9 events in the region shown, and 1.8 ± 0.5 events in the final signal box. From studies of a $K_L \to e^+e^-\gamma\gamma$ Monte Carlo simulation there is less than 1 event expected in the final signal box from this background, but a better measurement of the branching ratio of this decay mode is needed before an exact prediction can be made [10]. There are 25 events in the region shown, in agreement with the Monte Carlo simulation for the K_{e3} backgrounds. No data events fall in the signal box.

This search differs from previous searches in that we calculate the $K_L \to \pi^0 e^+e^-$ sensitivity using a K_L decay with a two-electron final state, namely, $K_L \to e^+e^-\gamma$. By normalizing to the decay $K_L \to e^+e^-\gamma$, systematic errors due to the uncertainty in electron identification efficiency are reduced. The uncertainty in the branching ratio of $K_L \to e^+e^-\gamma$ [reported at $(9.1 \pm 0.5) \times 10^{-6}$ in Ref. [11]] introduces a 5.5% systematic error. To check for any unforeseen systematic error due to normalizing a decay with two photons in the final state to a decay with one photon in the final state we use as a cross check the number of reconstructed $K_L \to \pi^0\pi^0_D$ decays (with three photons in the final state) found in the same normalization trigger. The analyses were done as similarly as possible given the kinematic differences in the three decay modes. These two normalization modes give consistent sensitivities, and the final mass distributions for both modes are shown in Fig. 3.

After all cuts there were 255 $K_L \to e^+e^-\gamma$ events, and the acceptance calculated by Monte Carlo simulation is 1.50%. Given that the prescale on the Dalitz trigger was 14, the total number of K_L's between $35\,\mathrm{GeV}/c$ and $220\,\mathrm{GeV}/c$ in momentum decaying between 90 and 160 m downstream of the target was $[26.5 \pm 1.6(\mathrm{stat}) \pm 1.5(\mathrm{syst})] \times 10^9$. Based on 194 $K_L \to \pi^0\pi^0_D$ events, 5% of which are estimated to be from background processes,

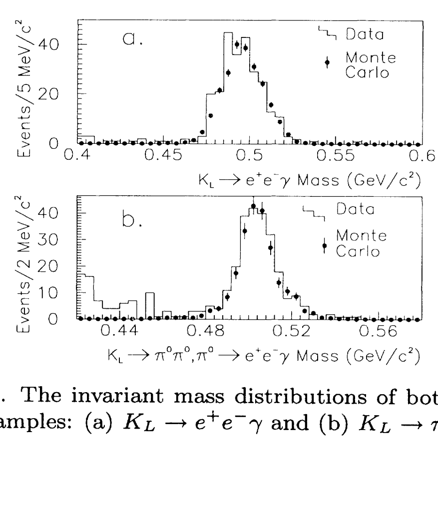

FIG. 3. The invariant mass distributions of both normalization samples: (a) $K_L \to e^+e^-\gamma$ and (b) $K_L \to \pi^0\pi^0_D$.

the total number of K_L's in the same momentum range and decay volume was predicted to be $[29.5 \pm 2.1(\text{stat}) \pm 0.4(\text{syst})] \times 10^9$. Since the $K_L \to \pi^0 e^+ e^-$ decay is more similar kinematically to the decay $K_L \to e^+ e^- \gamma$ than the decay $K_L \to \pi^0 \pi^0_D$, we use the more conservative $K_L \to e^+ e^- \gamma$ flux to set our upper limit on the branching ratio.

To measure the $K_L \to \pi^0 e^+ e^-$ acceptance the Monte Carlo simulation must assume a particular decay distribution. For the final result the decay distribution generated in the Monte Carlo simulation was flat over the available phase space. If the dominant intermediate process is $K_L \to \pi^0 \gamma^*$, however, a vector interaction for the decay may be more appropriate. A vector interaction introduces a dependence on M_{ee} which is different from phase space, so a check was made on the $K_L \to \pi^0 e^+ e^-$ acceptance as a function of M_{ee}. Figure 4 shows the $K_L \to \pi^0 e^+ e^-$ acceptance as a function of generated M_{ee}, as well as the two different generated M_{ee} spectra: one for a vector interaction, and one for a flat phase space decay. The relative independence of the acceptance as a function of M_{ee} ensures that this limit does not depend strongly on whether or not the decay is described by a phase space or a vector interaction. In fact, the overall $K_L \to \pi^0 e^+ e^-$ acceptance differs by only $(1.9 \pm 0.2)\%$ between the two different decay distributions. A 1.9% systematic error is therefore assigned to the overall $K_L \to \pi^0 e^+ e^-$ acceptance to account for this difference.

Other sources of systematic error considered were the effects of uncertainties in the understanding of the calorimeter, such as the effect of varying the energy scales, lead-glass gains and pedestals, and the effects of momentum scale and resolution uncertainties in the charged spectrometer. The total systematic error on the single event sensitivity from these sources is 0.8%. All sources of error were added in quadrature to obtain a total systematic error of 5.9%.

The $K_L \to \pi^0 e^+ e^-$ acceptance is $[2.06 \pm 0.04(\text{syst})]\%$, and therefore the single event sensitivity to the $K_L \to \pi^0 e^+ e^-$ decay in this experiment is $[1.84 \pm 0.10(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-9}$. We set a 90% confidence level upper limit of 4.3×10^{-9} which takes into account the combined systematic and statistical error on the single event sensitivity. Because of the difference in acceptances between this measurement and the most sensitive previous experiment [7], this limit represents an even greater improvement in searching for CP-violating components of this decay than the single event sensitivities would suggest, given that the CP-violating processes are expected to be modeled by a vector interaction. The combined limit, using the previous best two results [7,8] and the one reported here, is 1.8×10^{-9} at the 90% confidence level.

To reach the expected level predicted by the standard model, future searches will need to reduce accidental activity in the detector, improve electron/pion discrimination, and accurately predict the resulting semileptonic background level. To determine the different signal contributions to the decay an analysis of the Dalitz plot will be necessary, and a flat acceptance over M_{ee} will be important. A future experiment (E799, Phase II) is scheduled with significant improvements in electron/pion discrimination, beam collimation, photon energy resolution, and total K_L flux.

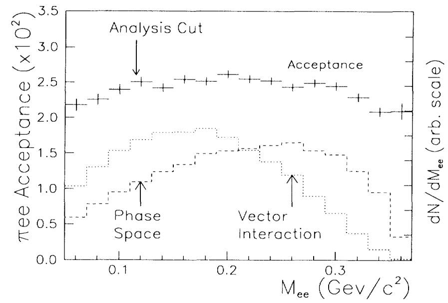

FIG. 4. The acceptance as a function of M_{ee} after all cuts but the one requiring $M_{ee} > 115\,\text{MeV}/c^2$, and the generated M_{ee} spectra for two different models of $K_L \to \pi^0 e^+ e^-$ decay: a vector interaction and phase space.

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