Search for the Rare Decay $K_L \to \pi^0 e^+ e^-$

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The KTeV/E799 experiment at Fermilab has searched for the rare kaon decay $K_L \to \pi^0 e^+ e^-$. This mode is expected to have a significant *CP* violating component. The measurement of its branching ratio could support the standard model or could indicate the existence of new physics. This Letter reports new results from the 1999–2000 data set. One event is observed with an expected background at 0.99 ± 0.35 events. We set a limit on the branching ratio of 3.5×10^{-10} at the 90% confidence level. Combining with the previous result based on the data set taken in 1997 yields the final KTeV result: $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ at 90% C.L.

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The decay $K_L \to \pi^0 e^+ e^-$ has long been studied in the context of standard model *CP* violation (CPV) and has also been of recent interest in certain new physics scenarios. In the standard model, there are direct and indirect CPV contributions to the amplitude, plus an interference term [1–3]. The indirect component is known from the measurement [4] of $\mathrm{BR}(K_S \to \pi^0 e^+ e^-)$ and appears to dominate. The direct component has been estimated to be about $(3\text{–}6) \times 10^{-12}$, and the two CPV contributions together give $\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}}$ in the range $(8\text{–}45) \times 10^{-12}$. There is also a *CP* conserving amplitude through $\pi^0 \gamma^* \gamma^*$ states which can be determined from measurements of $K_L \to \pi^0 \gamma\gamma$ [5,6]. In recent work, Buchalla, D'Ambrosio, and Isidori [7] argue that the *CP*-conserving contribution is negligible. They predict a standard model branching ratio $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) \sim 3 \times 10^{-11}$, dominated by CPV, with a 40% contribution from direct CPV, largely as a result of the the interference term.

Many scenarios for physics beyond the standard model lead to significant enhancements of $\mathrm{BR}(K_L \to \pi^0 e^+ e^-)$. In a large class of supersymmetry (SUSY) models, an enhancement of up to 5 times the standard model expectation is considered likely [8]. The existing experimental limit has been used to constrain squark masses [9] and SUSY contributions [10] to the charge asymmetry in $K^\pm \to \pi^\pm \ell^+ \ell^-$. The implications of a specific model with extra dimensions for $K_L \to \pi^0 e^+ e^-$ and related processes have been investigated in Ref. [11].

The existing experimental upper limit [12] on $\mathrm{BR}(K_L \to \pi^0 e^+ e^-)$ of 5.1×10^{-10} at the 90% confidence level (C.L.) is based on the 1997 KTeV dataset. In this Letter, we present an improved limit based on data collected during 1999–2000.

At KTeV, 800 GeV/c protons from the Fermilab Tevatron were directed onto a BeO target to create two parallel K_L beams. The beams entered a 65 m long vacuum tank, which defines the fiducial volume for accepted decays. Charged particles were detected by two pairs of drift chambers separated by an analysis magnet providing a transverse momentum kick of 0.150 GeV/c.

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Photon vetoes, which are positioned around the vacuum decay region and the spectrometer, vetoed particles outside the fiducial region of the drift chambers. The KTeV detector is further described in Ref. [13].

Powerful discrimination against charged pions, which could fake electrons, was provided by a set of transition radiation detectors (TRDs) behind the drift chambers. Each of the eight planes was composed of a polypropylene felt radiator paired with a double-plane multiwire proportional chamber containing an 80%–20% admixture of xenon and CO_2. TRD cuts resulted in a pion rejection factor of about 50:1, as measured in a sample of $K_L \to \pi^\pm e^\mp \nu$ decays. These cuts give a total TRD efficiency for two-electron final states of 88.6%. A more detailed description of the TRD may be found in Ref. [14].

Downstream of the TRDs were the trigger hodoscopes, followed by the CsI electromagnetic calorimeter, which had an energy resolution $\sigma(E)/E = 0.45\% \oplus 2\%/\sqrt{E(\mathrm{GeV})}$.

A detailed package of Monte Carlo (MC) simulation routines, including GEANT-based shower simulations, was used to study detector geometry and performance, as well as various trigger and analysis selection criteria. The programs were also used to simulate background events and tailor cuts to optimize the signal to background ratio.

The $K_L \to \pi^0 e^+ e^-$ final state consists of two photons, which come from the π^0 decay, and two electrons. $K_L \to \pi^0 e^+ e^-$ candidates exhibit the following signature: two tracks of opposite charge originating from a common vertex, and depositing all of their energy in the calorimeter; and two other clusters in the calorimeter, which, when taken as photons originating from the vertex, have a mass consistent with the π^0 mass.

$K_L \to \pi^0 \pi^0_D$ events, where π^0_D indicates the pion Dalitz decay $\pi^0 \to e^+ e^- \gamma$, are used to measure the K_L flux and normalize the acceptance calculation. This mode has a signature similar to $K_L \to \pi^0 e^+ e^-$, with an additional photon.

Recorded $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \pi^0_D$ events satisfied the following trigger requirements. The hodoscope planes and drift chambers must have had hits consistent with the passage of two oppositely charged particles. There must not have been hadronic showers in the calorimeter, and the event must have deposited little energy in the photon vetoes. There must have been a minimum number of clusters in the calorimeter with energy greater than 1 GeV, as determined by the hardware cluster counting system.

In the offline event reconstruction and analysis, events are required to satisfy further selection criteria. The charged tracks must point to calorimeter clusters. To identify these tracks as electrons, the ratio of the energy of the matched cluster as measured in the CsI (E) to track momentum as measured by the drift chambers (p) must lie in the range $0.95 < E/p < 1.05$. The track positions must have sufficient clearance from the CsI edges. The decay vertex (Z_{vtx}) has to be within the vacuum decay volume: $96\ \mathrm{m} < Z_{vtx} < 158\ \mathrm{m}$. The reconstructed kaon momentum is required to be between 20.3 and 216 GeV/c. Tracks are required to be well separated (greater than 1 cm apart at the first drift chamber) and the opening angle between the two tracks has to be larger than 2.25 mrad in the laboratory frame.

Further selection cuts for the $K_L \to \pi^0 \pi^0_D$ sample included requirements on the invariant masses of the $e^+ e^- \gamma$, $\gamma\gamma$, and $e^+ e^- \gamma\gamma\gamma$ combinations, and on the momentum transverse to the K_L flight direction, $p_\perp$. A well-reconstructed kaon should have a $p_\perp$ close to zero. Using the calculated acceptance and known branching ratio for $K_L \to \pi^0 \pi^0_D$ decays, the total number of K_L decays in the data sample is found to be $(349.0 \pm 2.8_{\mathrm{stat}} \pm 21.6_{\mathrm{syst}} \pm 11.8_{\mathrm{BR}}) \times 10^9$.

Several backgrounds with the $e^+ e^- \gamma\gamma$ final state exist and can mimic the $K_L \to \pi^0 e^+ e^-$ signal. The first source of background is $K_L \to \pi^+ \pi^- \pi^0$, where both charged pions shower in the calorimeter and appear to be electrons. To remove this background, the mass of the event, under the hypothesis that the tracks were pions, is required to exceed 520 MeV/c^2.

The second source of background is $K_L \to \pi^0 \pi^0$ and $K_L \to \pi^0 \pi^0 \pi^0$ with one or two Dalitz decays of a π^0 and with one or more photons undetected. To ensure that all K_L decay products are observed, $p_\perp^2 < 1000\ (\mathrm{MeV}/c)^2$ is required. Additional background events of this type are removed by requiring that the invariant mass of the two electrons, m_{ee}, exceeds 140 MeV/c^2. However, there are some backgrounds involving two π^0_D decays in which only one electron and one positron are reconstructed with a high mass. These events might also include coincident accidental activity. These background events are rejected by requiring that m_{ee} be less than 362.7 MeV/c^2.

The third source of background is $K_L \to \pi^\pm e^\mp \nu$, where the pion fakes an electron by showering in the calorimeter, and photons are radiated by the electron or are accidentals. This background is rejected by examining the response of the TRDs for both tracks.

After these cuts are applied, the single largest remaining background is the radiative Dalitz decay $K_L \to e^+ e^- \gamma\gamma$ with invariant mass of the two photons, $m_{\gamma\gamma}$, consistent with the π^0 mass. These events come from both internal and external bremsstrahlung; both contributions were studied in Ref. [15].

In Fig. 1, $m_{\gamma\gamma}$ is plotted against the invariant mass of the four-particle system, $m_{ee\gamma\gamma}$. The $m_{\gamma\gamma}$ is determined under the assumption that the photons came from the charged vertex, while $m_{ee\gamma\gamma}$ is calculated using the "neutral vertex," found by applying the π^0 mass constraint to the photon energies and positions in the calorimeter. Better $m_{ee\gamma\gamma}$ resolution is achieved for the signal Monte Carlo simulation using the neutral vertex, but this procedure gives the incorrect mass for the $K_L \to e^+ e^- \gamma\gamma$ background, resulting in the diagonal swath in Fig. 1.

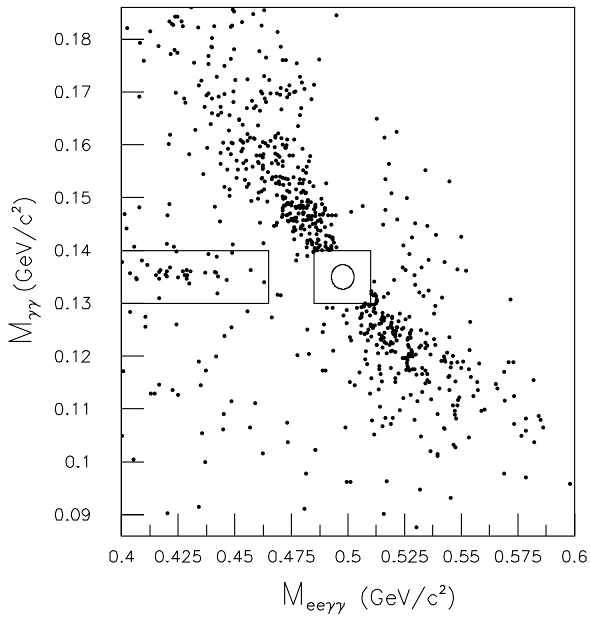

FIG. 1. $m_{\gamma\gamma}$ (charged vertex) vs $m_{ee\gamma\gamma}$ (neutral vertex) for the data after all cuts have been applied except for the phase space cuts. The regions appearing in the figure are discussed in the text, and signal events in the center box have not been plotted. Masses are in GeV$/c^2$.

There are several distinctive regions in the $m_{\gamma\gamma}$ vs $m_{ee\gamma\gamma}$ plane. The "box" is the blind region, which was covered up until cuts were finalized in order to minimize human bias. It spans $130 < m_{\gamma\gamma} < 140$ MeV$/c^2$ and $485 < m_{ee\gamma\gamma} < 510$ MeV$/c^2$. The ellipse inside the box is the signal region, which spans $\pm 2\sigma$ in the $K_L \to \pi^0 e^+ e^-$ signal Monte Carlo $m_{ee\gamma\gamma}$ and $m_{\gamma\gamma}$ distributions. In the $m_{ee\gamma\gamma}$ direction, the ellipse is ± 5.02 MeV$/c^2$ wide, and in the $m_{\gamma\gamma}$ direction it is ± 2.32 MeV$/c^2$ wide. The rectangular "strip" to the left of the box is dominated by backgrounds from $K_L \to \pi^0_D \pi^0_D$ and $K_L \to \pi^0 \pi^0_D \pi^0_D$ decays with accidental π^0. Missing particles in these decays cause the reconstructed mass $m_{ee\gamma\gamma}$ to be low. Because these backgrounds accumulated in the strip, this region is not considered in the background estimation described below.

In the background estimation, the data in Fig. 1, outside the strip and box regions, is fit to the sum of planar parts and the $K_L \to e^+ e^- \gamma\gamma$ sample:

$$f(m_{ee\gamma\gamma}, m_{\gamma\gamma}) = A_0 + A_{\gamma\gamma} m_{\gamma\gamma} + A_{ee\gamma\gamma} m_{ee\gamma\gamma} + A_g g(m_{ee\gamma\gamma}, m_{\gamma\gamma}),$$

where $g(m_{ee\gamma\gamma}, m_{\gamma\gamma})$ is the $K_L \to e^+ e^- \gamma\gamma$ distribution in the $m_{\gamma\gamma}$ vs $m_{ee\gamma\gamma}$ plane. The parameters A_i were the parameters from the fit. The non-$K_L \to e^+ e^- \gamma\gamma$ background was well modeled with first-order terms. The estimated background in the signal ellipse is 38.11 ± 1.67 events, with 0.27 ± 0.03 event contribution from non-$K_L \to ee\gamma\gamma$ backgrounds.

In order to reduce this background, phase space cuts [16] are applied to the data. The phase space variables with the best discrimination against $K_L \to e^+ e^- \gamma\gamma$ are $|y_\gamma|$ and $\theta_{\min}$. The variable y_γ is the cosine of the angle between the π^0 decay axis and the sum of the momenta of the two electrons, calculated in the center of mass of the photon pair. In the signal mode, $|y_\gamma|$ is uniformly distributed because the pion has spin zero, but in $K_L \to e^+ e^- \gamma\gamma$, the distribution is peaked at one. The variable $\theta_{\min}$ is the minimum angle between any photon and any electron in the kaon rest frame. It provides good separation because, in $K_L \to e^+ e^- \gamma\gamma$, a radiated photon typically has a small angle with respect to the electron from which it originated, while in $K_L \to \pi^0 e^+ e^-$, $\theta_{\min}$ is nearly flat. Distributions for $|y_\gamma|$ and $\theta_{\min}$ in $K_L \to \pi^0 e^+ e^-$ and $K_L \to e^+ e^- \gamma\gamma$ Monte Carlo simulation as well as the data appear in Fig. 2.

To find the optimum value for the phase space cuts, the values of both cuts are varied, and for each set the expected background and signal acceptance are calculated. The expected 90% C.L. branching ratio limit is determined for each set of cuts by generating many virtual experiments and using the Feldman-Cousins technique [17]. It was assumed that only events due to background are observed. The optimized phase space cuts are taken to be the values that yield the lowest expected branching ratio limit.

The phase space cuts selected $\theta_{\min} > 0.362$ and $|y_\gamma| < 0.745$, which reduce the expected background in the

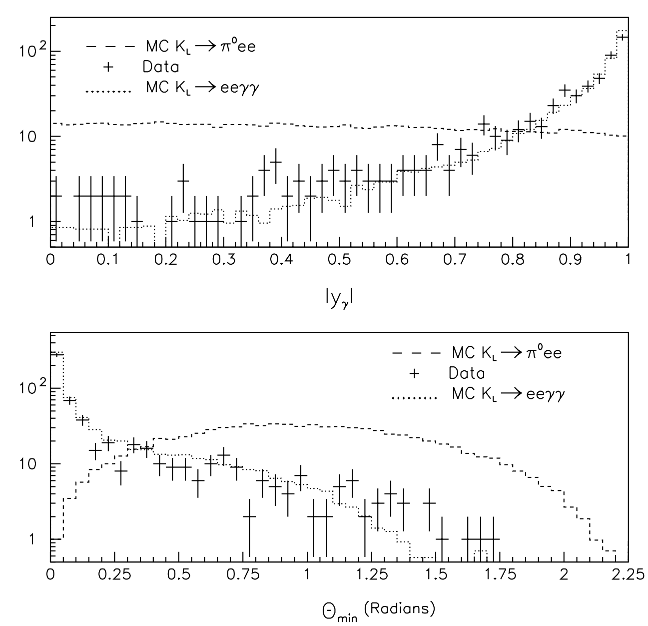

FIG. 2. $|y_\gamma|$ (top panel) and $\theta_{\min}$ (bottom panel) distributions for $K_L \to \pi^0 e^+ e^-$ MC simulation and $K_L \to e^+ e^- \gamma\gamma$ data and MC simulation. $K_L \to e^+ e^- \gamma\gamma$ events come from inside the swath but outside the box. $K_L \to \pi^0 e^+ e^-$ MC calculations are from inside the box, and the normalization is arbitrary. $\theta_{\min}$ is in radians.

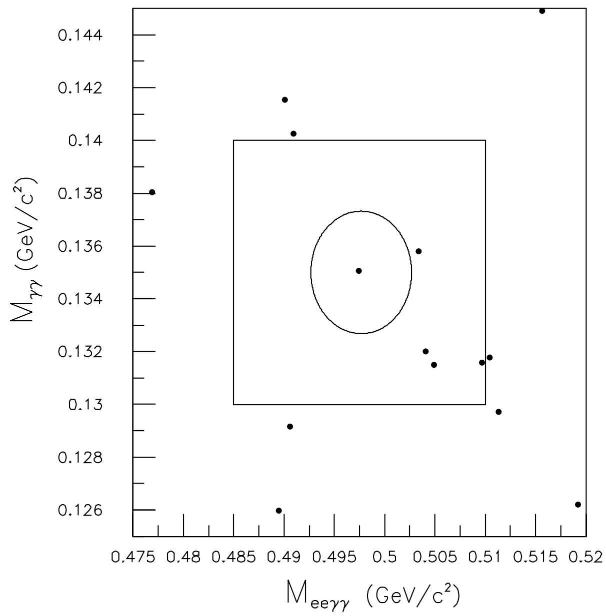

FIG. 3. $m_{\gamma\gamma}$ vs $m_{ee\gamma\gamma}$ in GeV/c^2 for the data after all cuts have been applied. The box is open and one event appears within the signal ellipse, with a background of 0.99 ± 0.35 events.

signal ellipse to 0.99 ± 0.35, with a contribution of 0.84 ± 0.22 from $K_L \to ee\gamma\gamma$. The expected background in the box from all sources is 3.9 ± 1.4 events, with 2.9 ± 0.75 events due to $K_L \to ee\gamma\gamma$. The phase space cuts reduce the signal acceptance by 27%, giving a final acceptance, assuming uniform three-body phase space, of $(2.749 \pm 0.013)\%$, and a single event sensitivity of 1.04×10^{-10}. The acceptance for this analysis is about 30% less than the acceptance for our earlier result. The acceptance loss is due to tighter TRD, phase space, and mass cuts, which were needed to reduce backgrounds associated with an increased level of accidental activity.

When the box in Fig. 1 was opened (Fig. 3), one event was observed in the signal ellipse and five total in the box. Taking the expected background into account, we determine at the 90% C.L. $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) < 3.50 \times 10^{-10}$. Combining this with the previous result yields the final KTeV result: $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ at 90% C.L.

If instead of a uniform three-body phase space distribution for the signal mode we assume a vector interaction model for the direct CPV part of the decay and allow for form factors as in [12], we find for the combined 1997 and 1999 data samples a 90% C.L. upper limit of $\mathrm{BR}(K_L \to \pi^0 e^+ e^-) < 3.4 \times 10^{-10}$. If the decay $K_L \to \pi^0 e^+ e^-$ is saturated by the direct CPV component, we constrain the Wolfenstein Cabibbo-Kobayashi-Maskawa (CKM) parameter $|\eta| < 3.3$ at the 90% C.L. Although other measurements yield a more stringent constraint on $|\eta|$, it is important to make a variety of measurements in both the kaon system and the B system to determine if the CKM parameters are consistent.

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