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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 $\times 10^{-10}$ at the 90% confidence level. Combining with the previous result based on the dataset taken in 1997 yields the final KTeV result: 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 more recently been of 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, 2, 3]. The indirect component is known from the measurement [4] of BR($K_S \to \pi^0 e^+ e^-$) and appears to dominate. The direct component has been estimated to be about 3 to 6 $\times 10^{-12}$, and the two CPV contributions together give BR$(K_L \to \pi^0 e^+ e^-)_{CPV}$ in the range 8 to 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 $BR(K_L \to \pi^0 e^+ e^-) \sim 3 \times 10^{-11}$, dominated by CPV, with a 40% contribution from direct CPV, through the interference term.

Observation of $K_L \to \pi^0 e^+ e^-$ at rates substantially higher than Standard Model expectations would signal new physics. In a large class of SUSY models, a branching ratio enhancement of up to five times the Standard Model expectation is considered likely [8], but values as high as 10^{-10} are not entirely ruled out. The existing experimental limit [9] has been used to constrain squark masses [10] and SUSY contributions [11] 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 [12].

The existing experimental upper limit on BR($K_L \to \pi^0 e^+ e^-$) of 5.1 $\times 10^{-10}$ at the 90% confidence level (CL) 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 Tevatron were directed onto a BeO target to create two parallel K_L beams. The beams entered a 65m 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. Photon vetoes positioned around the vacuum decay region and the spectrometer vetoed particles escaping the drift chambers. The KTeV detector is further described in [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 were over 94% efficient for electrons. A more detailed description of the TRD may be found in [14].

Downstream of the TRDs were the trigger hodoscopes. The trigger required hits in the hodoscope planes and the spectrometer consistent with the passage of two oppositely charged particles. The trigger hodoscopes were followed by the CsI electromagnetic calorimeter [15], which had an energy resolution $\sigma(E)/E = 0.45\% \oplus 2\%/\sqrt{E(GeV)}$. Electrons were identified by requiring the ratio of the energy measured in the calorimeter (E) to the momentum as measured in the spectrometer (p) to be consistent with one; this cut rejected about 99.5% of charged pions.

A detailed package of Monte Carlo simulation routines 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 the addition of a photon.

Recorded $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\pi^0_D$ events satisfied the following trigger requirements. There must have been at least two separate track candidates in each drift chamber plane. 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 [16]. For $K_L \to \pi^0 e^+e^-$, this number was four clusters and for $K_L \to \pi^0\pi^0_D$ it was five.

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 m $< Z_{vtx} <$ 158 m. The recontructed 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 lab 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 $(349.0 \pm 2.8_{\rm stat} \pm 21.6_{\rm syst} \pm 11.8_{\rm BR}) \times 10^9$.

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, $p^2_\perp < 1000$ (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}, exceed 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 [17].

In Figure 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

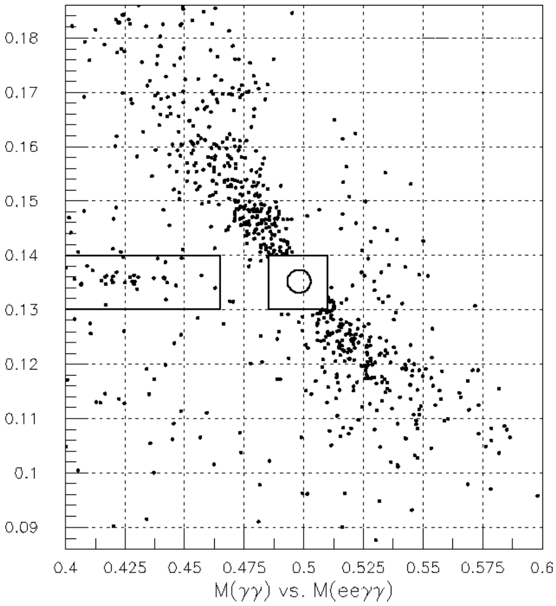

FIG. 1: $m_{\gamma\gamma}$ (charged vertex) vs. $m_{ee\gamma\gamma}$ (neutral vertex) for the data after all cuts have been applied except for the phase space cuts. The regions appearing in the figure are discussed in the text, and signal events in the center box have not been plotted. Masses are in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

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 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 Figure 1.

There are several distinctive regions in the $m_{\gamma\gamma}$ vs. $m_{ee\gamma\gamma}$ plane. In order to minimize human bias in the determination of the selection criteria, a blind analysis was performed. The box was the region covered up until cuts were finalized, and spans $130 < m_{\gamma\gamma} < 140$ MeV/c^2 and $485 < m_{ee\gamma\gamma} < 510$ MeV/c^2. The ellipse in the box is the signal region, which spans $\sim 2\sigma$ 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^0s. 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 Figure 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:

$$f\ (m_{ee\gamma\gamma}, m_{\gamma\gamma}) = \mathrm{A}_0 + \mathrm{A}_{\gamma\gamma} m_{\gamma\gamma} + \mathrm{A}_{ee\gamma\gamma} m_{ee\gamma\gamma} + \mathrm{A}_g\ \mathrm{g}(m_{ee\gamma\gamma}, m_{\gamma\gamma})$$

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 [18] are applied to the data. The location of these cuts is optimized by minimizing the expected 90% C.L. branching ratio limit of $K_L \to \pi^0 e^+e^-$, using the Feldman and Cousins [19] methodology. The expected branching ratio limit is computed by randomly generating a large ensemble of virtual experiments in which the known background sources are the only contributions to the observed number of events. The effect of the cuts on signal efficiency is also accounted for.

The phase space variables with the best discrimination against $K_L \to e^+e^-\gamma\gamma$ background are $|\ y_\gamma\ |$ and θ_{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 nearly 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 θ_{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 $K_L \to \pi^0 e^+e^-$, θ_{min} is nearly flat. Distributions for $|\ y_\gamma\ |$ and θ_{min} in $K_L \to \pi^0 e^+e^-$ Monte Carlo and $K_L \to e^+e^-\gamma\gamma$ data and Monte Carlo appear in Figure 2.

The optimized phase space cut values are $\theta_{min} > 0.362 \pm 0.017$ and $|\ y_\gamma\ | < 0.745 \pm 0.002$. These cuts reduce the expected background from 38.11 ± 1.67 events to 0.99 ± 0.35 with a signal loss of 27%. The signal acceptance, assuming uniform three-body phase space, is (2.749 ± 0.013)%, giving a single event sensitivity of 1.04×10^{-10}.

When the box in Fig. 1 was opened (Fig. 3), one event was observed in the signal ellipse. Taking the background level into account, we determine BR$(K_L \to \pi^0 e^+e^-) < 3.50 \times 10^{-10}$. Combining this with the previous result yields the final KTeV result: 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 [9], we find for the combined 1997 and 1999 data samples an upper limit of 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 CKM parameter $|\eta_{CKM}| < 3.3$. Although other measurements yield a more stringent constraint on

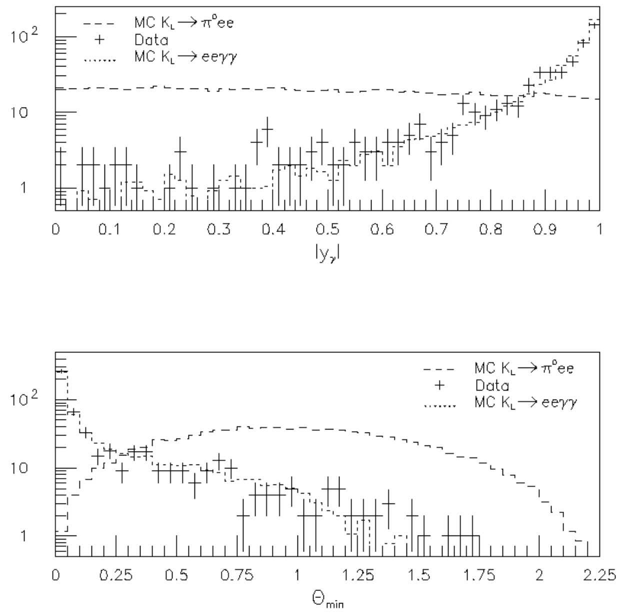

FIG. 2: $|\ y_\gamma\ |$ (top) and θ_{min} (bottom) distributions for $K_L \to \pi^0 e^+ e^-$ MC and $K_L \to e^+e^-\gamma\gamma$ data and MC. $K_L \to e^+e^-\gamma\gamma$ events come from inside the swath but outside the box. $K_L \to \pi^0 e^+ e^-$ MC are from inside the box, and the normalization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

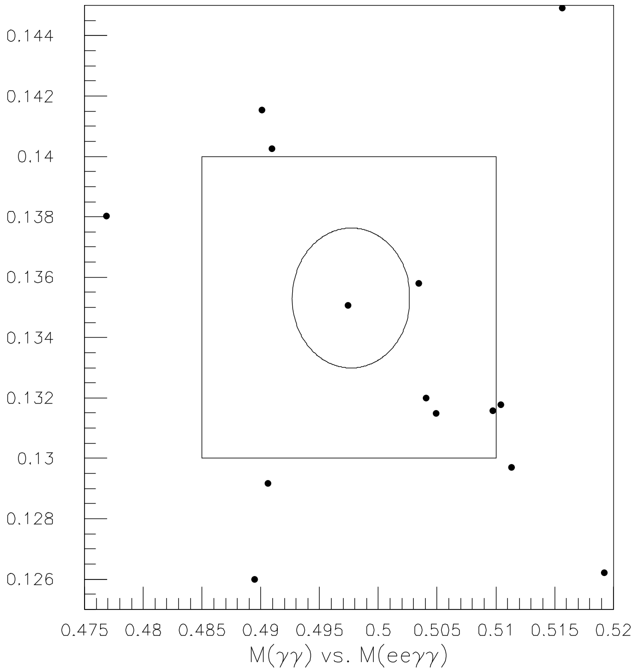

FIG. 3: $m_{\gamma\gamma}$ vs. $m_{ee\gamma\gamma}$ in GeV/c^2 for the data after all cuts have been applied. The box is open and one event appears within the signal ellipse, with a background of 0.99 ± 0.35 events

$|\eta_{CKM}|$, 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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