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

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We report on a search for the decay $K_L \to \pi^0 e^+ e^-$ carried out by the KTeV/E799 experiment at Fermilab. This decay is expected to have a significant *CP* violating contribution and the measurement of its branching ratio could support the Cabibbo-Kobayashi-Maskawa mechanism for *CP* violation or could point to new physics. Two events were observed in the 1997 data with an expected background of 1.06 ± 0.41 events, and we set an upper limit $\mathcal{B}(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$ at the 90% confidence level.

The decay $K_L \to \pi^0 e^+ e^-$ is interesting for the study of *CP* violation and can be used to search for new physics. Within the standard model there are three contributions [1] to this decay mode. The first is a directly *CP* violating contribution from electroweak penguin and $W^\pm$ box diagrams; only loops with t quarks, which have amplitudes proportional to η in the Wolfenstein parametrization [2], ultimately contribute. The second contribution is an indirectly *CP* violating contribution [3] due to the K_1 component of the K_L. Third, there is a *CP* conserving contribution proceeding through $\pi^0 \gamma^* \gamma^*$ intermediate states [4], which can be estimated from measurements [5] of the decay $K_L \to \pi^0 \gamma\gamma$. The total branching ratio in the standard model is in the range $(\sim 3-10) \times 10^{-12}$. Branching ratio predictions are higher in theories containing exotic particles that contribute to the penguin and box amplitudes. Although the minimal supersymmetric extension to the standard model permits only reductions in the

branching ratio [6], in other supersymmetric scenarios [7] it is reasonable for $\mathcal{B}(K_L \to \pi^0 e^+ e^-)$ to be as high as 2×10^{-11}, and possibly as high as 10^{-10}. The existing experimental branching ratio limit [8] is 4.3×10^{-9} at the 90% confidence level. This Letter presents an improved limit based on data taken by KTeV in 1997.

The major components of the KTeV detector, described in detail in Refs. [9–11], were a magnetic spectrometer for charged particle tracking, an electromagnetic calorimeter, and several veto counters to detect particles leaving the fiducial volume. The pure CsI electromagnetic calorimeter had an energy resolution for photons of $\sigma(E)/E = 0.45\% \oplus 2\%/\sqrt{E}$, where E is in GeV, and a π^0 mass resolution in $K_L \to \pi^+ \pi^- \pi^0$ of 1.31 MeV/c^2. The calorimeter was also used to identify electrons by comparing the energy deposit to the track momentum as measured by the spectrometer, rejecting 99.5% of all charged pions. Additional π/e separation was provided

with eight transition radiation detectors (TRDs) located behind the spectrometer [11,12]. Each TRD consisted of a polypropylene felt radiator followed by a two-plane multiwire proportional chamber using an $80\%/20\%$ Xe/CO_2 mixture. Pulse height readings from the planes were compared with pulse height spectra for pions from $K_L \rightarrow \pi^{\pm}e^{\mp}\nu$ decays that had been identified with kinematic and calorimeter requirements. Each pulse was assigned a confidence level for the hypothesis it came from a pion. The confidence levels for each of the planes where a hit was associated with a track were combined to yield an overall confidence level for the pion hypothesis. For this analysis, cuts giving a pion rejection factor of about 35:1 per pion track were used to maximize signal acceptance.

The trigger required hits in the trigger hodoscopes and in the drift chambers consistent with two coincident charged particles passing through the detector. The trigger system counted the number of isolated clusters of in-time energy in the calorimeter over ~1 GeV with a special processor [13]; at least four such clusters were required. The total energy deposited in the calorimeter was required to be over 28 GeV. Events with hadronic showers in the calorimeter were vetoed, as were events with activity in the photon veto system. Events that passed the hardware trigger requirements were reconstructed on-line and those that passed loose event topology and CsI electron identification cuts were recorded on tape.

The signature used to look for $K_L \rightarrow \pi^0 e^+ e^-$ in the detector was two tracks from oppositely charged particles with a common vertex that deposited all their energy in the calorimeter, plus two extra calorimeter clusters which, if interpreted as photons from the charged vertex, had $m_{\gamma\gamma} = m_{\pi^0}$. The decay $K_L \rightarrow \pi^0 \pi_D^0$, where π_D^0 denotes a pion with a subsequent $\pi^0 \rightarrow e^+ e^- \gamma$ (Dalitz) decay, was used to verify the acceptance calculation and to measure the number of K_L decays in the data sample. Its signature was similar to the signal mode's, but with an additional photon satisfying $m_{ee\gamma} = m_{\pi^0}$.

A detailed Monte Carlo simulation was used to determine the acceptances for the signal and normalization modes, allowing for detector geometry, trigger requirements, reconstruction efficiencies, and analysis cuts. It was also used to study background processes. The simulation generated kaon decays with the same energy and spatial distributions as the data and allowed for particle scattering and inelastic interactions with material in the beam line. At the highest kaon energies included in this analysis, a non-negligible K_S component appeared in decay volume and contributed to the $K_L \rightarrow \pi^0 \pi_D^0$ sample; this was reproduced by the simulation and was taken into account in determining the number of K_L decays.

Final event reconstruction was done after off-line calibration of the detector. Recorded events were required to satisfy basic quality requirements: the electrons were required to not have struck the calorimeter near the beam holes, and the track to cluster matching had to be un-

ambiguous. The reconstructed vertex was required to lie within the neutral beam and well within the vacuum decay region. The reconstructed kaon momentum was required to be between 20.3 and 216 GeV/c. Signals used in the trigger were required to lie within ranges where the simulation modeled the data well. The tracks were required to be more than 1 cm apart at the first drift chamber and have an angle over 2.25 mrad in the lab frame. The calorimeter cluster associated with each electron had to have an energy within $\pm5\%$ of the electron's momentum as measured with the spectrometer. Events with four clusters (including the two associated with tracks) found by the trigger cluster counter were used to search for the signal; events with five such clusters were used to identify $K_L \rightarrow \pi^0 \pi_D^0$.

The $K_L \rightarrow \pi^0 \pi_D^0$ sample was selected with requirements on reconstructed mass and total squared momentum transverse to the K_L flight direction ($P_\perp^2$), and had background of $(0.439 \pm 0.044)\%$. Using the acceptance and branching ratio, we determined that there were $(263.0 \pm 1.5_{\text{stat}} \pm 15.4_{\text{syst}} \pm 9.1_{\text{BR}}) \times 10^9$ K_L decays between 90 and 160 m from the target with K_L momentum between 20 and 220 GeV/c. The systematic uncertainty includes only effects not common to both signal and normalization mode, and the third uncertainty is due to uncertainties in $\mathcal{B}(K_L \rightarrow \pi^0 \pi^0)$ and $\mathcal{B}(\pi^0 \rightarrow e^+ e^- \gamma)$. The largest systematic uncertainty, $\pm4.9\%$, was from the change in acceptance when Monte Carlo events were reweighted to match the occupancy in the beam region of the first drift chamber for the normalization mode, where tracks are typically close to each other. Additionally, we assigned a $\pm3.1\%$ uncertainty corresponding to reasonable variations in the selection criteria.

Understanding and suppressing backgrounds are essential for the signal mode search. The first background was $K_L \rightarrow \pi^+ \pi^- \pi^0$ where both $\pi^{\pm}$ showered in the calorimeter; this was removed by requiring the reconstructed mass of the event, assuming that the tracks were created by pions, to be over 520 MeV/c^2.

The second background was $K_L \rightarrow \pi^0 \pi^0$ and $K_L \rightarrow \pi^0 \pi^0 \pi^0$ with subsequent $\pi^0 \rightarrow e^+ e^- \gamma$ decays. This was reduced by requiring the mass of the two electron system to be over 140 MeV/c^2. There remained some events with two π_D^0 decays where only one e^+ and one e^- were reconstructed with a high mass. These events could also have accidentally coincident activity. We rejected events with m_{ee} over 370 MeV/c^2. To ensure that we observed all the K_L decay products, we required that the $P_\perp^2$ be less than 1000 (MeV/c)^2.

The third major background was $K_L \rightarrow \pi^{\pm}e^{\mp}\nu$ with a pion that showered in the calorimeter, accompanied by coincident activity and/or photons radiated from the electron. This background limited previous searches [8], but was suppressed here with the TRDs. Tracks with TRD data that fit the pion hypothesis with nominally 4% confidence level or less were considered electrons; the actual rejection

factor was measured using a sample of $K_L \rightarrow \pi^{\pm} e^{\mp} \nu$ decays. This requirement was applied to both tracks for both normalization mode and signal mode; in the normalization mode $(94.5 \pm 2.2)\%$ of events passing all other selection criteria passed the TRD requirement.

Background from $K_S \rightarrow \pi^0 e^+ e^-$, assuming that $\Gamma(K_S \rightarrow \pi^0 e^+ e^-) \sim \Gamma(K^+ \rightarrow \pi^+ e^+ e^-)$, is expected to be $\mathcal{O}(10^{-3})$ events.

The limiting background was the radiative Dalitz decay $K_L \rightarrow e^+ e^- \gamma \gamma$ when $m_{\gamma\gamma} = m_{\pi^0}$. This background was predominantly internal bremsstrahlung events, but also includes $K_L \rightarrow e^+ e^- \gamma$ where an electron radiated a photon while passing through the detector. Both components are treated; details are in Ref. [10]. Figure 1 shows the distribution of reconstructed two photon mass, $m_{\gamma\gamma}$, vs reconstructed mass of the four particle system, $m_{ee\gamma\gamma}$, for data events passing all the selection criteria described above. The $m_{\gamma\gamma}$ was calculated assuming that the photons originated at the charged vertex. To the contrary, $m_{ee\gamma\gamma}$ was calculated using the π^0 mass and measured photon energies to determine the decay point. Use of this "neutral vertex" improved the $m_{ee\gamma\gamma}$ resolution, permitting a tighter search requirement on this parameter. The diagonal swath in Fig. 1 is from $K_L \rightarrow e^+ e^- \gamma \gamma$ decays, where the photons were incorrectly assumed to have come from a π^0.

Three regions are marked out in Fig. 1. To the left is the region $m_{\gamma\gamma} = 135 \pm 5$ MeV/c^2, $m_{ee\gamma\gamma} < 465$ MeV/c^2. Here the otherwise flat distribution of backgrounds from $K_L \rightarrow \pi^{\pm} e^{\mp} \nu$ and $K_L \rightarrow \pi_D^0 \pi_D^0$ decays with accidental π^0s and from $K_L \rightarrow \pi^0 \pi_D^0 \pi_D^0$ decays is peaked due to the π^0s in these backgrounds. This region was not used in estimating the background levels. The larger central box in Fig. 1 is the "blind" region ($m_{\gamma\gamma} = 135 \pm 5$ MeV/c^2, $485 < m_{ee\gamma\gamma} < 510$ MeV/c^2), which was blanked out until the analysis procedure and cuts were finalized to avoid human bias. This region was also ignored in the background estimation procedure. The smaller central box is the signal region ($m_{\gamma\gamma} = 135.20 \pm 2.65$ MeV/c^2, $m_{ee\gamma\gamma} = 497.67 \pm 5.00$ MeV/c^2), the size of which is roughly a $\pm 2\sigma$ range in the signal Monte Carlo.

To estimate the background in the signal region, we fit the distribution of events to $\max([B_0 + B_\pi m_{\gamma\gamma} + B_K m_{ee\gamma\gamma}], 0) + B_1 \mathcal{H}$, where $\mathcal{H}$ is the distribution in the $(m_{ee\gamma\gamma}, m_{\gamma\gamma})$ plane of $K_L \rightarrow e^+ e^- \gamma \gamma$ as determined from simulation, and B_i are the parameters of the fit. Empirically, the non-$K_L \rightarrow e^+ e^- \gamma \gamma$ background is well fit without second order terms. The estimated $K_L \rightarrow e^+ e^- \gamma \gamma$ background in the signal region of Fig. 1 is 36.9 ± 2.0 events. The only available method for suppressing this background is to apply phase space fiducial cuts [14]. The optimal cuts were found by minimizing
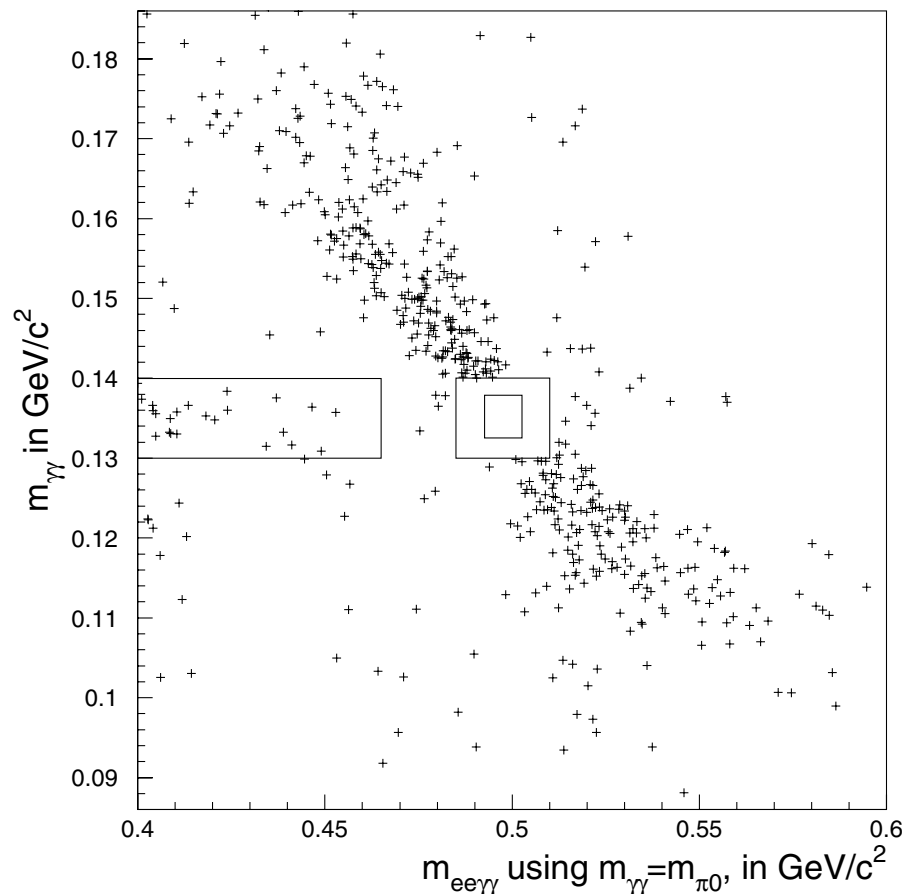

FIG. 1. $m_{\gamma\gamma}$ vs $m_{ee\gamma\gamma}$ for the data after all selection criteria except the phase space fiducial cuts designed to suppress $K_L \rightarrow e^+ e^- \gamma \gamma$. The boxes shown are described in the text; events within the central boxes have not been plotted.

the expected 90% C.L. limit on $\mathcal{B}(K_L \rightarrow \pi^0 e^+ e^-)$. That expected branching ratio limit was calculated using a hypothetical large ensemble of identical experiments in which the only processes contributing to the observed number of events were the known backgrounds. The impact of the cuts on the signal efficiency, as determined from the simulation, was taken into account.

The most powerful variables for separating the signal from the background were $|\cos(\theta_\pi)|$, where θ_π is the angle between the photons and the kaon in the π^0 rest frame, and θ_{min} is the minimum angle between any photon and any electron in the kaon rest frame. The $|\cos(\theta_\pi)|$, which is also the energy imbalance of the two photons, is a good discriminator because the comparatively high energy of the photon in a Dalitz decay causes this angle to be sharply peaked at $|\cos(\theta_\pi)| = 1$. In the signal mode, $|\cos(\theta_\pi)|$ is uniformly distributed because the pion is spinless. The minimum electron-photon angle is a good discriminator because radiated photons usually appear at a small angle to the electron from which they were emitted. In the signal, there is no particular relationship between the photons and the electrons and θ_{min} is nearly uniformly distributed. Another widely used variable is $|\Delta(\phi)|$, the angle between the plane of electrons and the photons. Again, this should be peaked near zero for $K_L \rightarrow e^+ e^- \gamma \gamma$ and uniformly distributed for $K_L \rightarrow \pi^0 e^+ e^-$. After optimization with $|\cos(\theta_\pi)|$ and θ_{min}, no additional rejection was obtained by cutting on $|\Delta(\phi)|$.

The optimal requirements are $|\cos(\theta_\pi)| < 0.788$ and $\theta_{min} > 0.349$; with these cuts, the expected $K_L \rightarrow e^+ e^- \gamma \gamma$ background was reduced to 0.91 ± 0.26 events with an $\sim 24\%$ signal loss. The signal acceptance was $(3.609 \pm 0.017 \pm 0.085)\%$, where the first uncertainty is from simulation statistics and the second is from the measurement of TRD efficiency in $K_L \rightarrow \pi^0 \pi_D^0$. The total expected background was 1.06 ± 0.41 events, corresponding (in the absence of signal) to an average expected branching ratio limit of 3.3×10^{-10}.

Several independent checks of the background were made. One important check was to verify that the distribution of the phase space variables in the diagonal swath of Fig. 1 matched expectations for $K_L \rightarrow e^+ e^- \gamma \gamma$ decay. The $K_L \rightarrow e^+ e^- \gamma \gamma$ branching ratio measured with this sample was consistent with experimental results [10,15] and theoretical expectations [14], and the spectra of m_{ee}, $m_{\gamma\gamma}$, and other kinematic variables were well simulated.

Figure 2 shows $m_{\gamma\gamma}$ vs $m_{ee\gamma\gamma}$ for data, including events in the former blind region, and the 1σ and 2σ C.L. contours of the Monte Carlo signal simulation. Two events exist in the signal region for the data. Allowing for the background [16] and its uncertainty [11], we set a 90% C.L. limit of 4.85 events. With the above acceptance, data set size, and background level, we set an upper limit $\mathcal{B}(K_L \rightarrow \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$ at the 90% C.L., which is 1 order of magnitude better than the previous result. This limit assumes a uniform three body phase
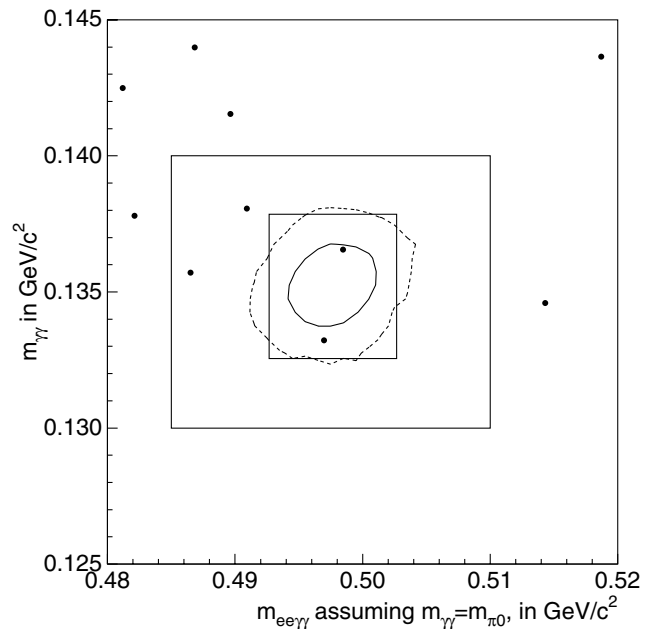

FIG. 2. As in Fig. 1, on an expanded scale around the signal region, for the data (dots) and signal simulation. The contours mark the 1σ and 2σ levels for the signal. All selection criteria have been applied.

space distribution for the signal mode. Alternatively, if the electron pair is the product of a single vector meson (as in the penguin and indirect CP violating terms) and we model the hadronic vertex with a form factor from $K_L \rightarrow \pi^\pm e^\mp \nu$ decay [17,18],

$$f_+(q^2) = f_+(0)\{1 + [0.0300 \pm 0.0016](q^2/m_\pi^2)\},$$

the 90% C.L. limit is $< 6.1 \times 10^{-10}$.

If the decay amplitude is saturated by the directly CP violating contribution, $|\eta| < 4.4$ at the 90% C.L., using Eq. (7) of [3]. While not yet as sensitive in probing the Cabibbo-Kobayashi-Maskawa parametrization as B decays, where recent indirect global analyses [19] find η to be below 1, measurements in the kaon system are a valuable test of whether the same parametrization is valid for both B and K decays. With substantially larger event samples, the use of analyses based on fitting the proper time, Dalitz variables, or decay asymmetries to observed events [3,20] may improve this limit.

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