First Observation of the decay $K_L \to \pi^0 e^+ e^- \gamma$

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The KTeV Collaboration

We report on the first observation of the decay $K_L \to \pi^0 e^+ e^- \gamma$ by the KTeV E799 experiment at Fermilab. Based upon a sample of 48 events with an estimated background of 3.6 ± 1.1 events, we measure the $K_L \to \pi^0 e^+ e^- \gamma$ branching ratio to be $(2.34 \pm 0.35 \pm 0.13) \times 10^{-8}$. Our data agree with recent $\mathcal{O}(p^6)$ calculations in chiral perturbation theory that include contributions from vector meson exchange through the parameter a_V. A fit was made to the $K_L \to \pi^0 e^+ e^- \gamma$ data for a_V with the result $-0.67 \pm 0.21 \pm 0.12$, which is consistent with previous results from KTeV.

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In this paper, we present the first observation of the decay mode $K_L \to \pi^0 e^+ e^- \gamma$. A previous search by the E162 experiment at KEK has established BR($K_L \to \pi^0 e^+ e^- \gamma$) $< 7.1 \times 10^{-7}$ at the 90% confidence level [1]. The $K_L \to \pi^0 e^+ e^- \gamma$ data presented in this paper were also used to measure the parameter a_V, which is an important ingredient in the calculation of the branching ratio of this decay mode using Chiral Perturbation Theory (CHPT). CHPT is a low energy effective theory of QCD which has been a very useful tool for describing kaon decays in which long distance effects are expected to dominate. An $\mathcal{O}(p^6)$ calculation using CHPT by Donoghue and Gabbiani [2] predicts a branching ratio for $K_L \to \pi^0 e^+ e^- \gamma$ of 2.4×10^{-8}, contrasted with 1.0×10^{-8} from the $\mathcal{O}(p^4)$ calculation. Our measurement can distinguish between these two predictions.

The rare decay $K_L \to \pi^0 e^+ e^- \gamma$ is intimately related to the decay $K_L \to \pi^0 \gamma\gamma$ via the internal conversion of one of the photons into an e^+e^- pair. The $\mathcal{O}(p^4)$ calculation of $K_L \to \pi^0 \gamma\gamma$ requires no free parameters, but the estimated branching ratio was found to be a factor of three lower than the measured value [3]. The CHPT calculation extended to $\mathcal{O}(p^6)$ was found to be able to reproduce the branching ratio as well as the distinctive $m_{\gamma\gamma}$ spectrum [4]. However, the cost was to introduce a free parameter into the theory, a_V, which parameterizes the contribution of vector meson exchange to the decay amplitude. The parameter a_V was estimated to be -0.96 in Reference [5] from fits to 2π and 3π decay data in the kaon system. A recent measurement of a_V by the KTeV experiment in the $K_L \to \pi^0 \gamma\gamma$ system finds a_V to be $-0.72 \pm 0.05 \pm 0.06$, and has confirmed that the shape of the $m_{\gamma\gamma}$ spectrum is reproduced by the theory [6].

The decay $K_L \to \pi^0 e^+ e^- \gamma$ is also interesting because of its relationship to the CP violating decay $K_L \to \pi^0 e^+ e^-$. Since a significant fraction of the total $K_L \to \pi^0 e^+ e^-$ amplitude proceeds through a CP conserving two photon intermediate state, $K_L \to \pi^0 \gamma^* \gamma^*$, it is essential to probe the $K_L \to \pi^0 e^+ e^- \gamma$ decay dynamics in order to better disentangle the CP conserving amplitudes from the CP violating ones in $K_L \to \pi^0 e^+ e^-$ [5]. Also, the rate of $K_L \to \pi^0 e^+ e^- \gamma$ is expected to be several orders of magnitude higher than the rate of the CP violating rare decay $K_L \to \pi^0 e^+ e^-$. In the soft photon region, it can be a source of background for the search for $K_L \to \pi^0 e^+ e^-$.

The data analyzed here were collected during the 1997 runs of E799. The KTeV detector itself is described in detail elsewhere [7]. The principal KTeV detectors used in this analysis include a pure CsI electromagnetic calorimeter, a nearly hermetic lead-scintillator photon veto system, and a charged particle spectrometer system.

The CsI calorimeter [8] is composed of 3100 blocks in a 1.9 m by 1.9 m array that is 27 radiation lengths deep. Two 15 cm by 15 cm holes are located near the center of the array for the passage of two neutral kaon beams. For electrons with energies between 5 GeV and 60 GeV, the calorimeter energy resolution was better than 1%. The position resolution for electromagnetic clusters in the calorimeter is approximately 1 mm.

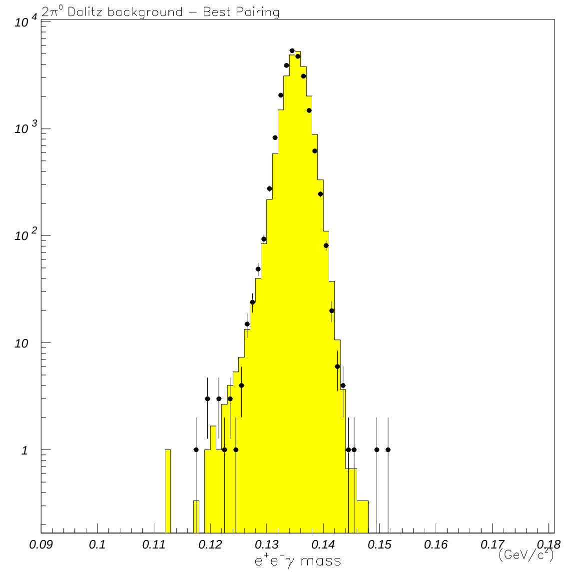

FIG. 1. The $m_{ee\gamma}$ distribution in E799 data (points) is compared with $K_L \to 2\pi^0_D$ Monte Carlo (histogram) including all cuts described in this analysis but for the cut against correctly paired $K_L \to 2\pi^0_D$ background. A small shift in the π^0 mass from calibration effects does not significantly contribute to systematic error in this measurement.

The charged particle spectrometer comprises four drift chambers. Two are located upstream and two downstream of an analyzing magnet with a transverse momentum kick of 0.205 GeV/c. Each drift chamber has four drift planes, with two planes oriented along the X direction and two along the Y direction transverse to the beams. Each drift plane is staggered by 0.5 cell with respect to its partner and was better than 99% efficient for recording hits from passing tracks. The momentum resolution was $0.38\% + 0.016\% \times p(GeV)$.

The fiducial decay volume is a vacuum tank of approximately 60 meters length located immediately upstream of the first drift chamber. The vacuum was maintained at better than 10^{-6} Torr for the data considered here. The charged particle spectrometer and vacuum tank are surrounded by 9 detectors arrayed along the length of the detector that veto stray photons.

The $K_L \to \pi^0 e^+ e^- \gamma$ final state consists of three photons, two of which proceed from π^0 decay, and two electrons. $K_L \to \pi^0 e^+ e^- \gamma$ events are recorded if they satisfy the following trigger requirements. There must be at least 2 hits in one of two scintillator hodoscopes and at least 1 hit in the other. In addition, there must be at least one hit in one of the two upstream drift chambers. The event must deposit more than approximately

25 GeV of total energy in the CsI calorimeter and deposit little energy in the photon vetoes. The event is vetoed if energy is deposited in a scintillator hadron veto located downstream of the CsI and a 10cm thick lead wall. The trigger includes a hardware cluster processor that counts the number of calorimeter clusters of contiguous blocks of CsI with energies above 1 GeV [9]. The total number of electromagnetic clusters at the trigger level in the CsI calorimeter is required to be greater than or equal to four. These trigger requirements also select $K_L \to 2\pi^0, \pi^0 \to e^+e^-\gamma$ ($K_L \to 2\pi^0_D$) events that we use as normalization for the $K_L \to \pi^0 e^+e^-\gamma$ signal.

In the offline analysis, we require exactly five reconstructed electromagnetic clusters in the CsI calorimeter each with energy greater than 2.0 GeV. Two of the clusters must match the extrapolated positions of the downstream components of the charged tracks. In order to identify the two charged tracks as electrons, the ratio of energy of the matched cluster as measured by the CsI (E) to track momentum as measured by the spectrometer (p) must lie in the interval $0.95 < E/p < 1.05$.

We calculate the kaon decay vertex by extrapolating track segments upstream of the analysis magnet back towards the target. The vertex position is then used to reconstruct a π^0 from each of the three possible $\gamma\gamma$ pairings. We rank the pairings by closeness of reconstructed mass to the nominal π^0 mass and designate the best $\gamma\gamma$ pair to be the reconstructed π^0. We also require that the best pairing choice satisfies $|m_{\gamma\gamma} - m_{\pi^0}| < 5.0$ MeV/c^2. In the normalization mode analysis, an additional requirement is made on the invariant mass of the $e^+e^-\gamma$ system; $|m_{ee\gamma} - m_{\pi^0}| < 6.0$ MeV/c^2. Events with missing momentum are supressed by a cut on the square of the transverse momentum of the reconstructed kaon defined with respect to the line connecting the kaon decay vertex and the target (p_T^2). We require $p_T^2 < 300(MeV/c)^2$. The decay vertex is required to be well within the vacuum decay volume. We require $98m < Z_{vtx} < 157m$ from target, and the reconstructed kaon momentum is required to be between 30 and 210 GeV/c.

$K_L \to 2\pi^0_D$ and $K_L \to 3\pi^0, \pi^0 \to e^+e^-\gamma$ ($K_L \to 3\pi^0_D$) decays are a source of background when photons are lost and/or mispaired. Backgrounds resulting from kaon decays with extra soft charged particles in the final state, such as $3\pi^0$ decays where two of the π^0 undergo Dalitz decay, are easily removed by discarding events with extra in-time hits in the region of the spectrometer upstream of the analysis magnet. Such events may fake two track events if soft tracks are swept out of the detector by the analysis magnet.

The $K_L \to 2\pi^0_D$ events are well simulated by our Monte Carlo as shown in Figure 1. The mass peaks agree to within 0.15% [7]. In order to remove $K_L \to 2\pi^0_D$ decays in the signal mode analysis we require the mass $m_{e^+e^-\gamma}$ not lie between 0.115 GeV/c^2 and 0.150 GeV/c^2. Mispaired $K_L \to 2\pi^0_D$ events, where the incorrect pairing of photons is chosen, constitute a possible background. We remove mispaired $K_L \to 2\pi^0_D$ events by considering each of the other possible photon pairings and discarding events which have reconstructed values of $m_{\gamma\gamma}$ and $m_{ee\gamma}$ that are consistent with $K_L \to 2\pi^0_D$ decay. Specifically, events are discarded if $\sqrt{(m_{\gamma\gamma} - m_{\pi^0})^2 + (m_{ee\gamma} - m_{\pi^0})^2} < 8$ MeV or 6 MeV in the case of the second best or worst pairing choice respectively.

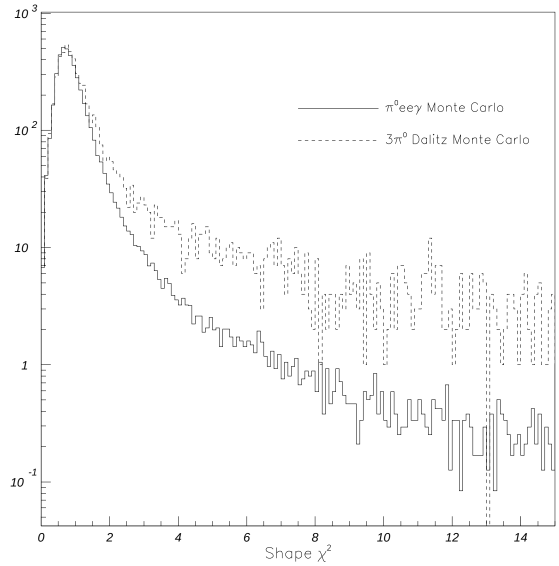

FIG. 2. The calorimeter shape χ^2 distribution for $K_L \to \pi^0 e^+e^-\gamma$ and $K_L \to 3\pi^0_D$ Monte Carlo samples. The larger tail in the $K_L \to 3\pi^0_D$ sample is indicative of a higher proportion of fusions.

$K_L \to 3\pi^0_D$ decays are the most difficult source of background to suppress in this analysis. These events can contribute to the background if two photons escaped detection or are fused in the calorimeter. In order to reduce backgrounds from $K_L \to 3\pi^0_D$ events with lost photons, we require less than 0.5 MIP activity in each of the photon veto detectors upstream of the spectrometer in the offline analysis. Some remaining $K_L \to 3\pi^0_D$ background results from events in which two or more photons fuse together in the CsI calorimeter. In order to reduce this background, a shower shape χ^2 was calculated for the distribution of energy deposited in the central crystals comprising the energy cluster compared to distribution of energy for a single photon. Figure 2 shows the distribution of shape χ^2 for both $K_L \to 2\pi^0_D$ and $K_L \to 3\pi^0_D$ Monte Carlo. By requiring the maximum χ^2 to be less than 5.0, we are able to effectively remove background due to $K_L \to 3\pi^0_D$ fusions.

A cut is also made on the kinematics of the $K_L \to 3\pi^0_D$ decay. The kinematical variables used are the 3γ invariant mass, $m_{3\gamma}$, and the square of the longitudinal momentum of the e^+e^- system in the kaon rest frame, $\mathcal{P}^2$. In order to make a cut in the $\mathcal{P}^2$-$m_{3\gamma}$ plane, a single variable κ was constructed from these two variables. The parameter $\kappa = \log \mathcal{P}^2 - 15.6 \times m_{3\gamma} + 4.6$, where the offset of 4.6 is chosen so that the the $K_L \to \pi^0 e^+ e^- \gamma$ Monte Carlo distribution in κ has its maximum at $\kappa = 0$. Figure 3 shows the distribution in κ for $K_L \to 3\pi^0_D$ in data and Monte Carlo and for $K_L \to \pi^0 e^+ e^- \gamma$ in Monte Carlo. The parameter κ is thus a convenient single variable kinematical discriminant between $K_L \to \pi^0 e^+ e^- \gamma$ signal and $K_L \to 3\pi^0_D$ background [7]. In order to remove the remaining $K_L \to 3\pi^0_D$ background, we require $\kappa < 0.5$.

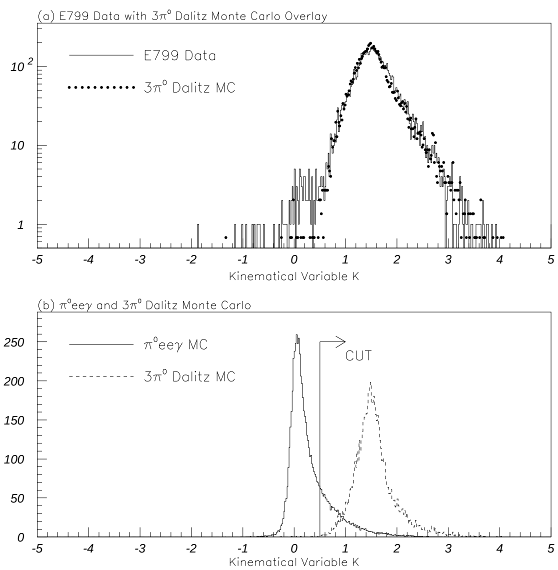

FIG. 3. The distribution of the kinematical variable described in the text, κ, for $K_L \to 3\pi^0_D$ and $K_L \to \pi^0 e^+ e^- \gamma$ Monte Carlo samples. The upper plot shows $K_L \to 3\pi^0_D$ in the E799 data overlaid with Monte Carlo. The lower plot shows $K_L \to 3\pi^0_D$ Monte Carlo with $K_L \to \pi^0 e^+ e^- \gamma$ Monte Carlo.

A more subtle background can come from $K_L \to e^+ e^- \gamma$ events accompanied by one or two bremsstrahlung photons plus accidental energy in-time with the event. In order to remove such events, a quantity D_{min} is calculated. The parameter D_{min} is the minimum distance between the position of an electron at the CsI extrapolated using the track segment upstream of the analysis magnet and the position of a photon at the CsI. The analysis requires $D_{min} > 1.25$ cm. This cut removes remaining backgrounds from brehmsstralung and is 99.5% efficient for keeping the $K_L \to \pi^0 e^+ e^- \gamma$ signal. Figure 4 shows the distribution of D_{min} for the data and signal Monte Carlo. Nine events are removed from the $K_L \to \pi^0 e^+ e^- \gamma$ sample by this cut at this stage.

The $m_{ee\gamma}$ distribution of the final event sample after making all cuts is shown at top in Figure 5, and the $m_{ee\gamma\gamma\gamma}$ distribution is shown below without the final mass cut. In order to select the final $K_L \to \pi^0 e^+ e^- \gamma$ event sample, a cut is made on the final state mass requiring that $m_{ee\gamma\gamma\gamma}$ lie between 490 MeV/c^2 and 505 MeV/c^2. We find a total of 48 candidate events. The estimated background in this sample from Monte Carlo include 1.6 ± 0.6 events from $K_L \to 2\pi^0_D$, 1.5 ± 0.9 events from $K_L \to 3\pi^0_D$, and 0.5 ± 0.1 events from $K_L \to e^+ e^- \gamma\gamma$ for a total of 3.6 ± 1.1 background events. The remaining background in the sidebands on the lower plot is due primarily to $K_L \to 2\pi^0_D$ decays that pass the cuts designed to reject Dalitz π^0 in the final state.

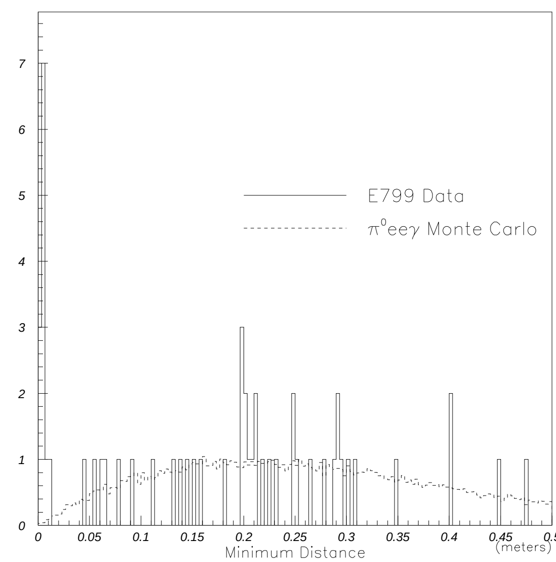

FIG. 4. The minimum distance between the extrapolated position of electrons at the CsI face using the tracks segments upstream of the analysis magnet and unmatched (photon) clusters is shown for the E799 data and for $K_L \to \pi^0 e^+ e^- \gamma$ Monte Carlo.

In order to determine the $K_L \to \pi^0 e^+ e^- \gamma$ branching ratio, we normalize the $K_L \to \pi^0 e^+ e^- \gamma$ event sample to the $K_L \to 2\pi^0_D$ event sample. The $K_L \to 2\pi^0_D$ events are selected by removing the requirements against $K_L \to 2\pi^0_D$ and requiring that $m_{e^+e^-\gamma}$ in the best pairing hypothesis lie within the window 0.129 GeV/c^2 to 0.141 GeV/c^2 while keeping all other cuts in place. We find 56467 $K_L \to 2\pi^0_D$ events in the E799 dataset with negligible background, corresponding to a kaon flux of 2.64×10^{11} kaons decaying in the E799 fiducial volume during the run.

The systematic uncertainty in this measurement is reduced since we are only sensitive to differences in the relative acceptance of the signal and normalization modes and not the absolute acceptance. The acceptances for the modes $K_L \to \pi^0 e^+ e^- \gamma$ and $K_L \to 2\pi^0_D$ are 0.72% and

0.95%, respectively.

The principal systematic uncertainties in this measurement come from the $K_L \to 2\pi^0_D$ branching ratio (3.4%), the $3\pi^0$ background MC statistics (3.0%), varying the a_V parameter in the $K_L \to \pi^0 e^+ e^- \gamma$ Monte Carlo (2.0%), varying the photon shape χ^2 cut (1.8%), varying the kinematic cut against $K_L \to 3\pi^0_D$ (0.6%), varying the cuts on the photon vetoes (0.5%), aperture effects (0.4%), varying the mass cuts (0.2%). The systematic uncertainties are added in quadrature, resulting in a total systematic uncertainty of 5.3%. We find the branching ratio to be $\mathrm{BR}(K_L \to \pi^0 e^+ e^- \gamma) = (2.34 \pm 0.35(stat.) \pm 0.13(syst.)) \times 10^{-8}$. This is consistent with the $\mathcal{O}(p^6)$ prediction and not with the $\mathcal{O}(p^4)$ CHPT prediction for the branching ratio. This measurement of $K_L \to \pi^0 e^+ e^- \gamma$ branching ratio also constitutes the first observation of this decay mode.

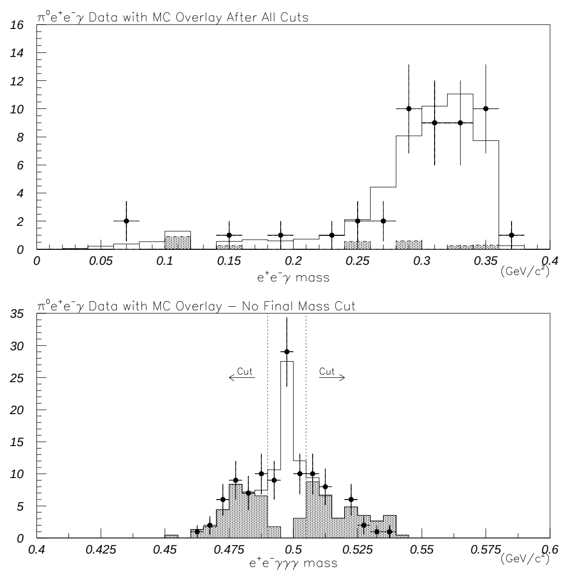

FIG. 5. The top plot shows the $m_{ee\gamma}$ distribution for the final $K_L \to \pi^0 e^+ e^- \gamma$ sample. The $m_{ee\gamma\gamma\gamma}$ distribution in E799 data (points) after all cuts except the final mass cut is shown below compared with signal+background Monte Carlo (histogram.) The solid histograms are from Monte Carlo, and the points with error bars are from the data. Background Monte Carlo alone appears in the shaded areas.

The parameter a_V was determined by maximum likelihood fit of the data to the Monte Carlo distributions in $Z = \frac{m^2_{ee\gamma}}{m^2_K}$, $Q = \frac{m^2_{ee}}{m^2_K}$, and $Y = \frac{E_\gamma - E_{ee}}{m_K}$, where E_γ and E_{ee} are the energies of the photon and the e^+e^- pair in the kaon CM frame respectively. The fitting method is described in more detail in [6]. The systematic error in this measurement was estimated by varying the amount of background in the data plot by an amount consistent with the statistical error in the background and by varying the analysis requirements. We measure a_V to be $-0.67 \pm 0.21(stat.) \pm 0.12(sys.)$. This result is consistent with the previous measurement by KTeV in the $K_L \to \pi^0 \gamma\gamma$ system.

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