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

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The recent discovery of a large CP violating asymmetry in $K_L \to \pi^+ \pi^- e^+ e^-$ mode has prompted us to search for the associated $K_L \to \pi^0 \pi^0 e^+ e^-$ decay mode in the KTeV-E799 experiment at Fermilab. In $2.7 \times 10^{11}$ $K_L$ decays, one candidate event has been observed with an expected background of 0.3 event, resulting in an upper limit for the $K_L \to \pi^0 \pi^0 e^+ e^-$ branching ratio of $6.6 \times 10^{-9}$ at the 90% C.L.

The discovery in the KTeV experiment of the $K_L \to \pi^+ \pi^- e^+ e^-$ decay mode [1] later confirmed by KEK-E162 and CERN-NA48 [2] together with the observation of a large CP violating asymmetry [3] in the angular distribution between the $e^+ e^-$ and $\pi^+ \pi^-$ planes, has generated interest in searching for $K_L \to \pi^0 \pi^0 e^+ e^-$. This Letter details the first attempt to detect this mode.

The $K_L \to \pi^+ \pi^- e^+ e^-$ decay can proceed at tree level via several amplitudes [4]. The main processes are (a) the CP violating bremsstrahlung process in which the $K_L$ decays into $\pi^+ \pi^-$ where one of the pions radiates a photon which internally converts into an $e^+ e^-$ pair, and (b) the CP conserving direct decay of the $K_L$ into a $\pi^+ \pi^-$ pair plus an $M1$ photon. Other smaller amplitudes include (c) the CP violating direct decay of the $K_L$ into a $\pi^+ \pi^-$ plus an $E1$ photon and (d) the “charge radius” amplitude describing the $K_L \to K_S$ transition by emission of a virtual photon followed by the CP conserving decay $K_S \to \pi^+ \pi^-$. This process is similar to the regeneration of $K_L \to K_S$ by scattering from atomic electrons, both of which are proportional to the mean squared charge radius of the neutral kaon. In contrast, the $K_L \to \pi^0 \pi^0 e^+ e^-$ decay, because the pions are neutral, has no bremsstrahlung amplitude. In addition, the direct emission of a $M1$ photon or an $E1$ photon is suppressed since gauge invariance and Bose statistics require a $\pi^0 \pi^0$ angular momentum of $l \geq 2$ [5].

A consequence of the suppression of the direct $M1$ and $E1$ emission processes and the absence of a bremsstrahlung process is that the $K_L \to \pi^0 \pi^0 e^+ e^-$ branching ratio is expected to be considerably smaller [6] than the $K_L \to \pi^+ \pi^- e^+ e^-$ branching ratio measured to be $3.2 \times 10^{-7}$ [1]. The $K_L \to \pi^0 \pi^0 e^+ e^-$ is predicted to be dominated by the CP conserving charge radius amplitude with additional contributions from the CP conserving $E2$ and CP violating $M2$ direct emission amplitudes. Theoretical estimates of the $K_L \to \pi^0 \pi^0 e^+ e^-$ branching ratio vary considerably from a vector meson dominance model estimate of $2.0 \times 10^{-8}$ [7] and chiral perturbation theory calculations of $1 \times 10^{-10}$ [8] and $2.3 \times 10^{-10}$ [6].
An observation of $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ would provide an indirect measurement of the $K_L \rightarrow \pi^0 \pi^0 \gamma$ branching ratio, a mode which is difficult to detect directly because of the serious backgrounds [9,10]. Observation of this mode would also allow investigation of chiral perturbation theory contributions to $O(p^4)$ and $O(p^6)$. The extra contributions of the full chiral perturbation calculations beyond that of the charge radius amplitude of Ref. [6] can complicate the extraction of this amplitude [6,8,11].

A search for the $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ decay mode has been conducted by the KTeV Collaboration using the 1997 E799 data set. In the E799 spectrometer configuration, two almost parallel neutral beams passed through the fiducial decay region of the KTeV spectrometer 95 m ≤ z ≤ 158 m downstream of a BeO production target. The beams were produced by $(3-5) \times 10^{12}$ 800 GeV/c protons per minute delivered in 20 sec spills incident at an angle of 4.8 mrad on a BeO target. The composition of the beams was mainly $K_L$'s and neutrinos with a small admixture of $\Lambda$'s, and $\Xi$'s. An integrated total of $2.7 \times 10^{11} K_L$ decays took place in the fiducial region while the trigger was live. The $K_L$ energies varied between 20 and 200 GeV with a mean of 70 GeV.

The KTeV spectrometer components which were used for the analysis of these decays consisted of four stations of drift chambers, two upstream and two downstream of an analysis magnet which provided a $p_t$ kick of 0.205 GeV/c for momentum determination of charged tracks. Downstream of the last drift chamber, in succession, were a charged particle trigger hodoscope which provided the first level trigger requirement of two charged tracks and a 3100 element pure CsI calorimeter for photon and electron id and energy determination. Surrounding the decay region and the elements of the detector were veto counters that detected charged and neutral particles that were not in the acceptance. The complete KTeV-E799 spectrometer configuration is described in Ref. [1].

The data were collected with a trigger which required two charged tracks in the drift chambers, four or more showers with energies ≥ 1 GeV and total energy in the CsI calorimeter be greater than 30 GeV and no significant energy be present in any segment of the veto counters surrounding the decay volume and spectrometer elements.

Events were selected off line that had six energy clusters in the CsI, two of which were associated with the $e^+ e^-$ pair. The $K_L$ decay vertices were determined by minimizing the $\chi^2$ of a fit which included the differences between the invariant mass of the secondary particles from the $\pi^0$ decays ($\gamma \gamma$ or $e^+ e^- \gamma$ in the case of modes with $\pi^0$'s undergoing Dalitz decay as discussed below) and $\pi^0$ mass together with the distance between the vertex and the $e^\pm$ tracks. The $\chi^2$ incorporated the measured uncertainties of the energies and positions of the photon clusters in the CsI and the uncertainties of the $e^\pm$ track position due to the drift chamber resolutions and multiple scattering. The event reconstruction checked all possible pairings of the photons to determine the best $\pi^0$ combinations.

In addition, a large $K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ sample (where $\pi^0_0$ indicates a Dalitz decay, $\pi^0 \rightarrow e^+ e^- \gamma$) was selected from events which had an $e^+ e^-$ pair and five CsI clusters unassociated with tracks. The $K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ signal was compared to a Monte Carlo of this mode incorporating detector acceptances, efficiencies and resolutions. Good agreement was observed in numerous kinematic distributions. Using the detector simulation of the $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ decays, a region of $0.493 \text{GeV/c}^2 \leq M_{\pi^0 \pi^0 e^+ e^-} \leq 0.501 \text{GeV/c}^2$ and $p_f^2(e^+ e^- \pi^0 \pi^0) \leq 1.5 \times 10^{-4} \text{GeV}^2/c^2$ was determined for the $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ search. The signal region contained 86% of the $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ decays (using the Sehgal model for our generated signal events). Here, $p_f^2(e^+ e^- \pi^0 \pi^0)$ was calculated relative to the vector from the center of the target to the $K_L$ decay vertex.

The most serious background to the $K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ mode resulted from $K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ decays in several ways: (a) one photon from a $\pi^0 \rightarrow \gamma \gamma$ decay converted internally or externally into an $e^+ e^-$ pair while one of the other photons in the decay fails to produce a detectable energy deposit in the CsI and the remaining four photons formed a good $\pi^0 \pi^0$ pair; (b) two of the six final state photons converted internally or externally into an $e^+ e^-$ pair and an $e^+$ and $e^-$ were lost; (c) one of the $\pi^0$ decayed into an $e^+ e^-$. In addition to the backgrounds from $K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ decays, $K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ decays with an extra accidental CsI energy cluster contributed a background. Finally, other backgrounds due to $K_L \rightarrow \pi^0 e^+ e^- \gamma$, $K_L \rightarrow \pi^0 \pi^0 \pi^0 \gamma$, and $K_L \rightarrow \pi^0 \pi^0 \pi^0 \gamma$ were found to be negligible due to physics cuts discussed below and to small branching ratios.

Special cuts were required to eliminate each type of background. $K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ decays in which two photons converted into $e^+ e^-$ pairs or one of the $\pi^0$'s decayed into two $e^+ e^-$ pairs were suppressed by rejecting events in which there were extra track segments upstream or downstream of the magnet. If a photon converted externally in the upstream spectrometer material, the resulting $e^+ e^-$ signal did not typically produce two reconstructed upstream track segments due to the small opening angle. If one member of the $e^+ e^-$ pair had low momentum and was swept out of spectrometer acceptance by the analysis magnet, no extra track segments were produced downstream of the magnet either. In these cases, the invariant mass of the observed charged track and the other photon from the $\pi^0$ decay was close to the mass of the parent $\pi^0$ and the event was rejected by cutting on the $\gamma e^\pm$ mass. Specifically, $K_L \rightarrow \pi^0 \pi^0 \pi^0 \pi^0$ decays with two photons from different $\pi^0$ converting to $e^+ e^-$ pairs and no extra track segments in the spectrometer were suppressed by rejecting events with two $e\gamma$ mass combinations with
0.115 GeV/c^2 ≤ M_{e\gamma} ≤ 0.145 GeV/c^2 and the remaining lepton's mass within 3 MeV/c^2 of the p\(^0\) mass. K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) decays where one photon converted into an e\(^+\)e\(^-\) pair and the other photon missed the calorimeter were rejected by calculating the missing photon energy and momentum assuming either (i) the missing photon went into the beam hole and had, in combination with the e\(^+\)e\(^-\), the p\(^0\) mass or (ii) the missing photon came from a K\(_L\) which had zero p\(_T^2\). If either, (i) M\(_{e^+e^-\gamma\gamma\gamma\gamma}\) ≤ 0.51 GeV/c^2 and p\(_T^2\)\(e^+e^-\gamma\gamma\gamma\gamma\gamma\) ≤ 0.0005 GeV^2/c^2 or, (ii) the e\(^+\)e\(^-\) plus missing gamma mass was greater than 0.065 GeV/c^2, the event was rejected.

To eliminate K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) decays where one photon converted into an e\(^+\)e\(^-\) pair and the other photon was lost due to coalescing with another photon in the CsI, all observed clusters were tested to see if any cluster could be due to an overlap of two photons. The energy of each observed cluster in turn was divided in various proportions and the two resulting clusters were used in a fit of the event to the K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) hypothesis. All possible combinations of all different clusters with different split fractions were combined with the other photons and the e\(^+\)e\(^-\) pair were considered to see if any combination was consistent with a K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) event. If the p\(^0\)\(\pi^0\)\(\pi^0\) invariant mass or the vertex \(\chi^2\) of a combination was consistent with a K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) decay, the event was rejected.

K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) decays in which one p\(^0\) decayed into an e\(^+\)e\(^-\) pair [BR(p\(^0\) → e\(^+\)e\(^-\)) = 6.09 × 10\(^{-5}\) [12]] were eliminated by requiring that M\(_{e^+e^-}\) ≤ 0.10 GeV/c^2. This cut also eliminated K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) decays in which one of the \(\pi^0\)s decayed into e\(^+\)e\(^-\) and one of the e\(^+\)e\(^-\) pairs had low energy and went undetected. K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) decays with an accidental cluster in the calorimeter were eliminated by requiring that M\(_{e^+e^-\gamma\gamma\gamma}\) ≤ 0.45 GeV/c^2. All e\(^+\)e\(^-\)\(\gamma\gamma\gamma\) combinations were checked and the mass cut was applied to the one with the smallest \(\chi^2\) for a K\(_L\) → p\(^0\)\(\pi^0\)\(\pi^0\) decay.
of the normalization events has been folded into the disagreement between the level of data and Monte Carlo simulation matching the simulation of this type of events. The trajectory passes through the center of the given beam hole. The solid dots are the data and the histogram is the Monte Carlo simulation of these events.

in Fig. 3 are the comparisons of the data and Monte Carlo simulations of the events vs $p_T^\gamma$ and $M_{\gamma\gamma\gamma\gamma}$.

An overall product of the acceptance and efficiency of 0.25% for the signal mode was obtained from a Monte Carlo simulation of $K_L \to \pi^0\pi^0e^+e^-$ mode using the model of Ref. [6] with a chiral perturbation parameter $w_s = 0.46$ [8]. Since estimations of $w_s$ from existing experimental data are indirect and model dependent, we have studied the variation of our acceptance as a function of $w_s$. We found that a simulation using a $w_s = 0.9$ gives a minimum acceptance of 0.205% in the model of Ref. [6] (and a maximum upper limit for $K_L \to \pi^0\pi^0e^+e^-$ branching ratio). By comparison, a simulation using phase space for the decay gave an acceptance of 0.29%. We have used the lower acceptance 0.205% for calculating the single event sensitivity using in determining a $K_L \to \pi^0\pi^0e^+e^-$ branching ratio upper limit.

$K_L \to \pi^0\pi^0\pi^0$ events with a missing $\gamma$ down the beam hole (which could be reconstructed as $K_L \to \pi^0\pi^0\pi^0_D$ using the technique for treating beam hole photons discussed above) were used as a normalization mode since they had the same trigger and analysis cuts as the signal mode. Figure 4 shows the mass distribution of these events compared to the Monte Carlo simulation. A distinct $K_L$ peak is reconstructed for the data with a resolution matching the simulation of this type of events. The disagreement between the level of data and Monte Carlo of the normalization events has been folded into the systematic error in the single event sensitivity.

A single event sensitivity of $1.71 \pm 0.06$(stat) $\pm 0.19$(syst) $\times 10^{-9}$ was calculated using the ratio of the $K_L \to \pi^0\pi^0e^+e^-$ signal efficiency to the $K_L \to \pi^0\pi^0\pi^0_D$ normalization sample efficiency, the $K_L \to \pi^0\pi^0\pi^0_D$ branching ratio of $7.59 \times 10^{-3}$ [13] and the observed $2234 K_L \to \pi^0\pi^0\pi^0_D$ normalization events of the type described in the previous paragraph. The observation of one event in the signal box resulted in an upper limit for BR ($K_L \to \pi^0\pi^0e^+e^-$) of $6.6 \times 10^{-9}$ at the 90% C.L. Using the ratio of the BR($K_L \to \pi^0\pi^0\gamma$) to BR($K_L \to \pi^0\pi^0e^+e^-$) of $= 50$ [6], our result is a factor of 10 more sensitive than the present upper limit of $5.6 \times 10^{-6}$ from a direct search [10] for $K_L \to \pi^0\pi^0\gamma$.

In conclusion, we have made the first attempt to detect the $K_L \to \pi^0\pi^0e^+e^-$ decay mode. We have established an upper limit of $6.6 \times 10^{-9}$ at the 90% C.L. (using a $w_s = 0.9$ in the model of Ref. [6]) which excludes the vector dominance model of Ref. [7] but does not quite reach the level of expected branching ratios predicted by the more recent models of Refs. [6,8].

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