Fermilab FERMILAB-CONF-04-481-E KTeV DECEMBER 2004

$K_L^0 \to \pi^0 \ell\bar{\ell}$ Searches at KTeV

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There has been renewed interest in the CP violating rare decay modes $K_L^0 \to \pi^0 \ell\bar{\ell}$. Recent measurements, such as the BR($K_S^0 \to \pi^0 \ell^+\ell^-$) modes, along with theory have led to improved estimates of the CP violating (indirect and direct) and CP conserving contributions to the K_L^0 modes. The KTeV fixed-target experiment at Fermilab has conducted searches for the $K_L^0 \to \pi^0 \ell\bar{\ell}$ modes; current status of these upper limits along with the present status of the predicted branching ratios will be presented.

1. Introduction

The $K_L^0 \to \pi^0 \ell\bar{\ell}$ decays are of interest as probes to direct CP violation. The branching ratio for the fully neutral decay $K_L^0 \to \pi^0 \nu\bar{\nu}$ is dominated by short distance contributions, allowing theoretical determination with few uncertainties [1]. The branching ratios for the charged mode $K_L^0 \to \pi^0 \ell^+\ell^-$ decays have contributions from direct CP violating diagrams, as well as contributions from indirect CP violation and CP conserving diagrams. The CP conserving amplitude can be estimated from theory and from a measurement of the effective vector coupling, a_v, from $K_L^0 \to \pi^0 \gamma\gamma$ [2,3]. The recent measurements of the $K_S^0 \to \pi^0 e^+e^-$ [4,5] and $K_S^0 \to \pi^0 \mu^+\mu^-$ [6] modes provide a handle on estimating the CP violating contributions to the corresponding K_L decays $K_L^0 \to \pi^0 e^+e^-$ [7,8] and $K_L^0 \to \pi^0 \mu^+\mu^-$ [9]. The CP violating component to the branching ratios includes a direct, an indirect, and a signed interference term. Predictions for the CP violating components, as well as CP conserving part of the $K_L^0 \to \pi^0 \ell\bar{\ell}$ branching ratios, are listed in Table 1. Included in the table are the central values for the total branching ratios for $K_L^0 \to \pi^0 e^+e^-$ and $K_L^0 \to \pi^0 \mu^+\mu^-$ for positive and negative interference terms.

The $K_L^0 \to \pi^0 \ell\bar{\ell}$ family of decays presented in this article contain leptons and photons in the final state; the salient features of the KTeV apparatus for detecting these particles in KTeV will be described here. The plan view of the KTeV detector in the E799 configuration is shown in Fig. 1.

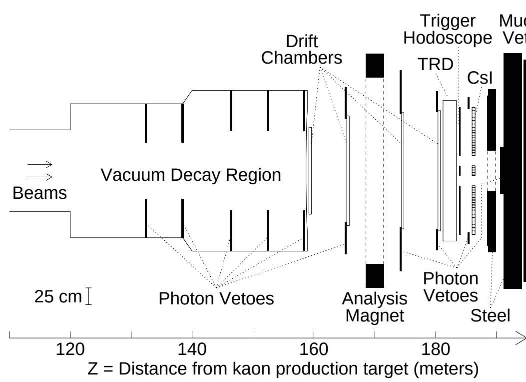

Figure 1. The plan view of the KTeV detector in the E799-II configuration.

Neutral beams are produced by striking a BeO target with an 800 GeV proton beam. The neutral beam passes through a series of collimators, a Pb absorber which converts photons, and a series of sweeping magnets which bend the charged particles out of the beamline. Two nearly parallel neutral kaon beams, composed mainly of

Table 1
Predictions for direct CP violation, indirect CP violation, a signed interference term and CP conserving contributions for B($K_L^0 \to \pi^0 \ell\overline{\ell}$) decays [2–9]. Also listed are the range of values for the branching ratios with positive or negative interference.

Mode	CPV Direct (10^{-12})	CPV Indirect (10^{-12})	CPV Interference (10^{-12})	CP Conserving (10^{-12})	Total (10^{-12})
B($K_L^0 \to \pi^0 \nu\overline{\nu}$)	30				30
B($K_L^0 \to \pi^0 e^+ e^-$)	4.7	17.2	9.4	(0.5-2)	32 (pos)
					13 (neg)
B($K_L^0 \to \pi^0 \mu^+ \mu^-$)	1.8	8.8	3.3	5.2	19 (pos)
					13 (neg)

kaon and neutrons with a small contamination of hyperons, then enter the 65m vacuum decay region where approximately 5% of the kaons decay. The range of K_L^0 momenta is 20-200 GeV/c. The charged spectometer consists of 4 planar drift chambers, two located upstream and two downstream, of an analysis magnet which imparts a transverse momentum kick to the charged particles. The magnetic kick was 205 MeV/c during the 1997 running period and 150 MeV/c for 1999 running. A pure CsI calorimeter provides electron identification and photon energy measurements. Additional electron identification information comes from a set of 8 transition radiation detectors (TRD). Muons are identified with two banks of orthogonal scintillation counters located downstream of 3m of filter steel. Photon veto detectors line the vacuum decay region and the perimeters of the drift chambers and CsI and form the defining aperture of the fiducial region.

For the rare decay program, the KTeV experiment collected $2.7 \times 10^{11} K_L^0$ decays during 1997 and $3.6 \times 10^{11} K_L^0$ decays 1999. The $K_L^0 \to \pi^0 \nu\overline{\nu}$ ($\pi^0 \to e^+ e^- \gamma$) limit presented here uses the 1997 data; the trigger for this mode was prescaled during the 1999 run. The $K_L^0 \to \pi^0 e^+ e^-$ analysis described here yields a combined limit based on both the 1997 and 1999 data sets. The $K_L^0 \to \pi^0 \mu^+ \mu^-$ analysis uses the 1997 data set only. The 1999 data are currently being analyzed for this mode.

2. $K_L^0 \to \pi^0 \nu\overline{\nu}$

While the $K_L^0 \to \pi^0 \nu\overline{\nu}$ mode is compelling because it is predominantly direct CP violating, it is experimentally challenging. The more prevalent decay mode with $\pi^0 \to \gamma\gamma$ has significant backgrounds because the kinematics make it difficult to reconstruct the event. If the Dalitz decay of the π^0 is used to tag the event, the decay vertex helps constrain the event but there is a factor of ~ 100 reduction in acceptance due to the branching ratio and the detector geometry. KTeV has set branching ratio limits using both π^0 decay modes.

The measurement using $\pi^0 \to \gamma\gamma$ is based on a dedicated special run in which a single kaon beam was used and events with high transverse momentum were selected. The $K_L^0 \to \pi^0 \nu\overline{\nu}$ ($\pi^0 \to \gamma\gamma$) analysis used a special 1 day run which corresponded to $6.8 \times 10^7 K_L^0$ decays. After all cuts, the single event sensitivity (SES) is 4.0×10^{-7}. One event is found in the signal region, which is consistent with the expectation from neutron interactions in material in the detector. Assuming the event is signal, we set an upper limit of $B(K_L^0 \to \pi^0 \nu\overline{\nu}, \pi^0 \to \gamma\gamma) < 1.6 \times 10^{-6}$ (90% C.L.) [10]. This represents a first time measurement using this decay chain.

Using the full KTeV 1997 data set with the Dalitz decay tag, the SES for $K_L^0 \to \pi^0 \nu\overline{\nu}$ is 2.6×10^{-7} after all cuts and after correcting for the Dalitz decay branching ratio. A plot of the transverse momentum of the data along with overlays from signal Monte Carlo and Monte Carlo from the most prevalent backgrounds ($\Lambda \to$

$n\pi^0$ and $\Xi \to \Lambda\pi^0$) is shown in Fig. 2; there are no events in the signal region. The upper limit set using the Dalitz decay of the π^0 is $B(K_L^0 \to \pi^0\nu\overline{\nu}, \pi^0 \to e^+e^-\gamma) < 5.9 \times 10^{-7}$ (90% C.L.) [11]. Assuming experimental inputs for the top and W masses and the Wolfenstein parameter A, the branching ratio limit implies $\eta < 52$.

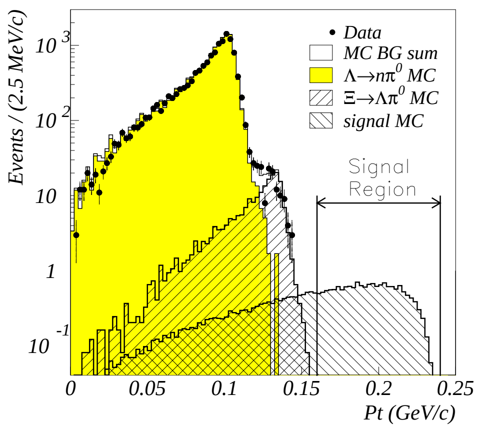

Figure 2. Pt distribution for $K_L^0 \to \pi^0\nu\overline{\nu}$ ($\pi^0 \to e^+e^-\gamma$) with all cuts except the Pt cut. Signal and background Monte Carlo are overlayed on data. There are no events in the signal region.

3. $K_L^0 \to \pi^0 e^+e^-$

Although the decay $K_L^0 \to \pi^0 e^+e^-$ is a fundamentally easier mode to select because the final state can be fully reconstructed, it is not a pure direct CP violating decay and it has a serious background from $K_L \to e^+e^-\gamma\gamma$. The indirect CP violating and CP conserving amplitudes are comparable in size to the direct CP violating contribution and must be understood before the direct CP violation component can be determined.

The background limiting mode to the decay $K_L^0 \to \pi^0 e^+e^-$ comes from the radiative Dalitz decay, $K_L \to e^+e^-\gamma\gamma$, which KTeV also has measured using the 1997 data set. The signal region yielded 1988 events with a background estimate of 76.6 ± 3.3 events. The resulting branching ratio, with a 5 GeV photon energy cutoff, is $B(K_L \to e^+e^-\gamma\gamma, E_\gamma \leq 5GeV) = (6.31 \pm 0.14(stat.) \pm 0.42(syst.)) \times 10^{-7}$. In addition to $K_L \to e^+e^-\gamma\gamma$, there are backgrounds from radiative $K_L \to \pi e\nu$ decay with an accidental photon, $K_L \to \pi e\nu$ decay with an accidental π^0, $3\pi^0$ ($2\pi^0$) decay in which one(two) pion(s) Dalitz decays, and $K_L \to \pi^+\pi^-\pi^0$ decay with $\pi^\pm$ misidentified as $e^\pm$. The modes which contain a Dalitz decay are easily rejected by cutting on the invariant mass of the e^+e^- pair. Modes in which charged pions mimic electrons are reduced through the excellent π/e separation in the calorimeter and TRDs.

Event selection criteria include requiring that the e^+e^- came from a good vertex and that the photons form a π^0. The event also is required to have small transverse momentum squared (Pt^2) with respect to the kaon direction.

The remaining background after all cuts have been applied comes from $K_L \to e^+e^-\gamma\gamma$, which is reduced with cuts on kinematic variables. One such variable, $cos(\Theta_\pi)$ (also denoted as y_γ), is the direction of the photon with respect to the direction of the π^0 (defined by a momentum vector opposite the e^+e^- pair) in the pion rest frame. This variable is flat for $K_L^0 \to \pi^0 e^+e^-$ decays since the π^0 is a spinless particle and the photons emerge back to back, while it is peaked near 0 for $K_L \to e^+e^-\gamma\gamma$ since the non-bremsstrahlung photon tends to go off in the direction opposite the electron-positron pair. A second variable that is used to distinguish signal from background is Θ_{min}, the angle between the photon and the nearest e^+ or e^-. This variable is flat for the signal mode and peaked near 0 for the bremsstrahlung photon in $K_L \to e^+e^-\gamma\gamma$. A plot of $|cos(\Theta_\pi)|$ and Θ_{min} for signal and background Monte Carlo and for data is also shown in Fig. 3. The cuts on these kinematic variables are optimized to yield the lowest expected branching fraction limit.

Fig. 4 shows the 2γ invariant mass versus the $K_L \to e^+e^-\gamma\gamma$ invariant mass with all cuts applied except those specific to suppressing $K_L \to e^+e^-\gamma\gamma$. The long box is populated by $K_L \to$

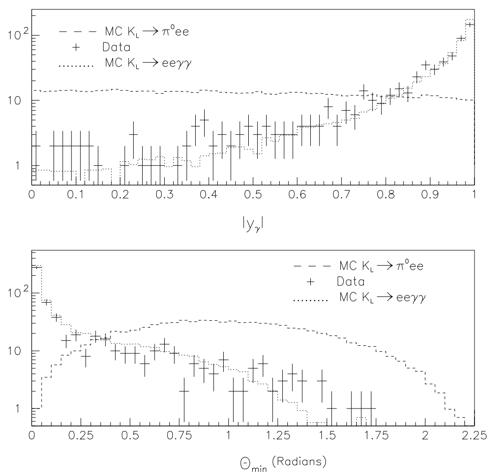

Figure 3. Kinematic variables $|y_\gamma|$ and Θ_{min} for signal and background Monte Carlo and for data. The variable $|y_\gamma|$ is equivalent to $|cos(\Theta_\pi)|$.

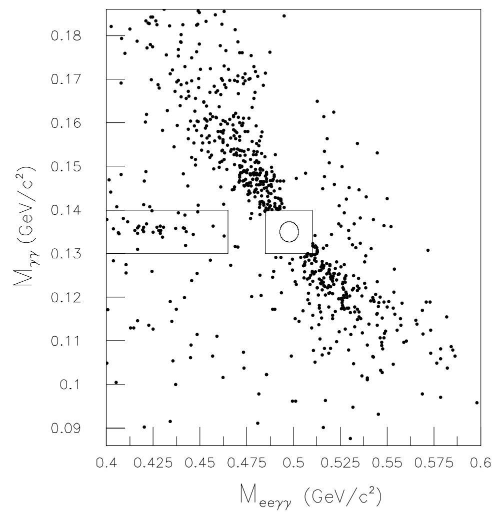

Figure 4. Reconstructed $M(2\gamma)$ versus $M(K_L \to e^+e^-\gamma\gamma)$ invariant masses with all cuts applied except kinematic cuts suppressing $K_L \to e^+e^-\gamma\gamma$. The $\pm 2\sigma$ ellipse inside the small box hides the signal region.

$\pi^0\pi^0\pi^0$ event fragments in which one $\pi^0 \to \gamma\gamma$ while the other two π^0s Dalitz decayed. Events in the low M($K_L \to e^+e^-\gamma\gamma$) and low M($2\gamma$) region are from $K_L \to \pi e \nu$ decays with accidental γs in which the π is misidentified. The band near the signal region is $K_L \to e^+e^-\gamma\gamma$. The small ellipse is the $\pm 2\sigma$ signal region. The box surrounding the ellipse is a study region. A Monte Carlo background estimate predicts 0.99 ± 0.35 events in the signal elipse. After all cuts, the signal acceptance, assuming uniform 3-body phase space, is $(2.749 \pm 0.013)\%$, giving a single event sensitivity of 1.04×10^{-10}. This acceptance is $\sim$30% lower than in the 1997 analysis because backgrounds were higher, requiring tighter cuts on TRD response, phase space and invariant mass. Fig. 5 reveals the signal ellipse after all cuts have been applied. There is 1 event observed in the signal region which is consistent with background. We quote an upper limit [12] for the 1999 analysis of $B(K_L^0 \to \pi^0 e^+e^-) < 3.50 \times 10^{-10}$ (90% C.L) [13]. The final combined upper limit (1997 + 1999) is $B(K_L^0 \to \pi^0 e^+e^-) < 2.8 \times 10^{-10}$ (90% C.L) [13]. If we assume that the only contribution to the branching ratio comes from direct CP violation and we take the experimental inputs of m_t, m_W, and the Wolfenstein paramter A, we find $\eta < 3.3$.

4. $K_L^0 \to \pi^0\mu^+\mu^-$

Like the electron mode, the decay $K_L^0 \to \pi^0\mu^+\mu^-$ is a probe of direct CP violation, although the direct CP violating component is somewhat smaller than the CP conserving component. In addition to the challenges of measuring a small branching ratio, there is potential background from $K_L \to \mu^+\mu^-\gamma\gamma$. The QED prediction for the branching ratio is $(9.1 \pm 0.78) \times 10^{-9}$. The KTeV experiment made the first observation of this mode in the 1997 data set. Four events were found within the signal region, significantly above the predicted background level of 0.155 ± 0.081 event. In order to compare this with the QED prediction, the branching ratio is calculated with a 1 MeV/c^2 cutoff in the 2γ invariant mass during Monte Carlo generation and is found to be $B(K_L \to \mu^+\mu^-\gamma\gamma, M_{\gamma\gamma} > 1\ MeV/c^2) =$

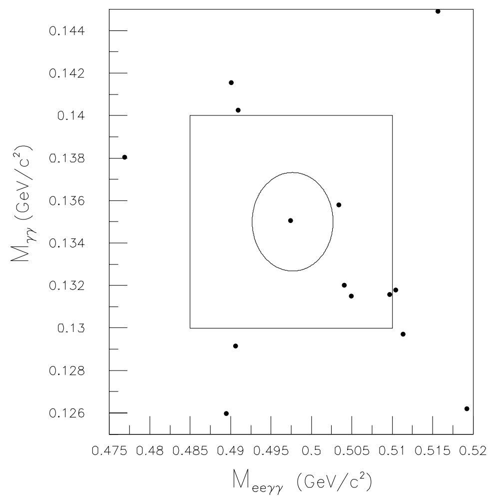

Figure 5. Reconstructed $M(2\gamma)$ versus $M(K_L \to e^+e^-\gamma\gamma)$ invariant masses after all cuts are applied. The small ellipse is the signal region.

$(10.4^{+7.5}_{-5.9}(stat.) \pm 0.7(syst.)) \times 10^{-9}$, which is consistent with theoretical prediction.

For the $K_L^0 \to \pi^0\mu^+\mu^-$ mode, the event selection requires that 2 photons form a π^0 and that a good vertex is reconstructed from two oppositely charged tracks which leave minimum ionizing deposits (MIP) in the calorimeter and fire the muon counters. Backgrounds come from pion punch-through from $K_L \to \pi^+\pi^-\pi^0$, pion decay-in-flight from $K_L \to \pi^+\pi^-\pi^0$, and $K_L \to \pi\mu\nu$ decay with 2 accidental photons. The most significant single background comes from $K_L \to \mu^+\mu^-\gamma\gamma$ and is estimated to be 0.373 ± 0.032 events in the signal region. The angular cuts which were used to reduce the background from $K_L \to e^+e^-\gamma\gamma$ decays in the $K_L^0 \to \pi^0e^+e^-$ analysis are less effective for the muon mode, since the photon and muon directions are less correlated and thus are not used in this analysis. The SES for this mode corresponds to a branching ratio of 7×10^{-10}. The total background contribution is expected to be 0.87 ± 0.15 events. The normalization mode for this measurement is $K_L \to \pi^+\pi^-\pi^0$. Fig. 6 shows the invariant mass spectrum. There are 2 events in the signal region which are consistent with background. We set an upper limit on the branching ratio of $B(K_L^0 \to \pi^0\mu^+\mu^-) < 3.8 \times 10^{-10}$ (90% C.L.) [14], which is an order of magnitude improvement over the previous measurement.

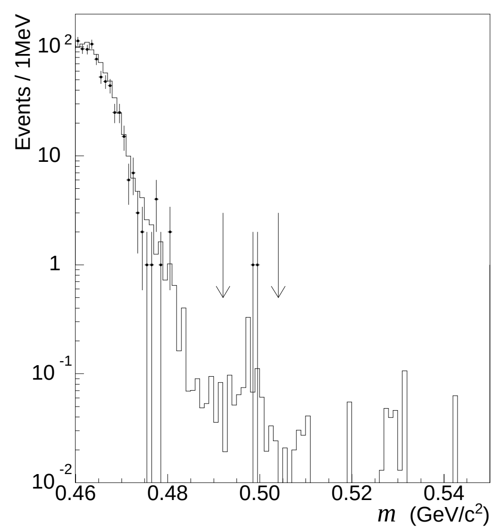

Figure 6. The $\mathrm{M}(K_L^0 \to \pi^0\mu^+\mu^-)$ invariant mass distribution. Signal and background Monte Carlo (histogram) are overlayed on data (dots). The signal region is indicated by arrows.

5. Summary and Future Outlook

KTeV has significantly improved the branching ratio measurements for the direct CP violating decays $K_L^0 \to \pi^0\nu\overline{\nu}$ (using both $\pi^0 \to \gamma\gamma$ and $\pi^0 \to e^+e^-\gamma$ modes), $K_L^0 \to \pi^0e^+e^-$, and $K_L^0 \to \pi^0\mu^+\mu^-$. A table summarizing recent predictions for these branching ratios along with the experimental upper limits are shown in Table 2.

The 1999 analysis of $\mathrm{B}(K_L^0 \to \pi^0\mu^+\mu^-)$ is needed to complete the set of $K_L^0 \to \pi^0\ell\overline{\ell}$ results. Just as in the $K_L^0 \to \pi^0e^+e^-$ mode, tighter cuts will need to be imposed to reduce the larger accidental backgrounds seen in that

Table 2
Predictions for $B(K_L^0 \to \pi^0 \ell\bar{\ell})$ decays, for positive and negative interference, and the experimental upper limits at the 90% confidence level.

Mode	Prediction	Experiment
$B(K_L^0 \to \pi^0 \nu\bar{\nu})$	3.0×10^{-11}	
$\pi^0 \to \gamma\gamma$		$< 1.6 \times 10^{-6}$ (1 day 1997)
$\pi^0 \to e^+e^-\gamma$		$< 5.9 \times 10^{-6}$(1997)
$B(K_L^0 \to \pi^0 e^+e^-)$	$(1.3 - 3.2) \times 10^{-11}$	$< 2.8 \times 10^{-10}$ (1997+1999)
$B(K_L^0 \to \pi^0 \mu^+\mu^-)$	$(1.3 - 1.9) \times 10^{-11}$	$< 3.8 \times 10^{-11}$ (1997)

data set. To reduce systematic uncertainties in our understanding of the muon system, the $K_L^0 \to \pi^0\mu^+\mu^-$ branching ratio will be normalized to $K_L \to \mu^+\mu^-\gamma$. The expected single event sensitivity for the combined 1997 and 1999 data is on the order of 1×10^{-10}.

Results from future $K_L^0 \to \pi^0 e^+e^-$ experiments E391a and KOPIO are eagerly awaited. The E391a experiment in Japan is currently taking data. The goal of that experiment is to achieve a sensitivity below 1.4×10^{-9} and to reach the level predicted by new physics (3.1×10^{-10}) [15]. Farther in the future, the KOPIO experiment, part of the RSVP program at Brookhaven National Laboratory, expects to detect about 50 events with a signal to background ratio of 2:1.

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