A new semileptonic K^0 decay mode $K_L \to \pi^\pm e^\mp \overset{(-)}{\nu} e^+ e^-$

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We observed a new kaon decay mode, $K_L \to \pi^\pm e^\mp \overset{(-)}{\nu} e^+ e^-$ for the first time. Based on the 19207 ± 25 events, we determined the branching fraction, $B(K_L \to \pi^\pm e^\mp \overset{(-)}{\nu} e^+ e^-; M_{e^+e^-} > 5\ \mathrm{MeV}/c^2, E^*_{e^+e^-} > 30\ \mathrm{MeV}) = (1.281 \pm 0.041) \times 10^{-5}$. This branching fraction agrees with a theoretical prediction based on the chiral perturbation theory (ChPT) calculated at $\mathcal{O}(p^4)$. Most of the kinematical distributions agree with the ChPT $\mathcal{O}(p^4)$ calculation.

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Semileptonic kaon decay, $K_L \to \pi^\pm e^\mp \overset{(-)}{\nu}$ (K^0_{e3}) has the largest decay rate in the neutral kaon decay, and its radiative mode, $K^0_{e3\gamma}$, has been extensively studied. In this letter, we introduce one more semileptonic kaon decay mode, $K_L \to \pi^\pm e^\mp \overset{(-)}{\nu} e^+ e^-$ (K_{e3ee}), that we observed for the first time, and present the measurement of its branching fraction. This decay mode is a radiative K^0_{e3} decay mode with a virtual photon ($K^0_{e3\gamma^*}$).

The amplitude of $K^0_{e3\gamma^{(*)}}$ consists of two parts. One is a part with inner bremsstrahlung from the pion or the electron (IB). The other is a part with a photon radiated from an intermediate hadronic state of K-π current, namely the structure dependent amplitude (SD) or the direct emission amplitude [1, 2]. Since the semileptonic K-π current obeys the low energy QCD, the model to describe the K-π current is important for both studying the K^0_{e3} decays themselves and understanding QCD. In fact, SD is studied to evaluate the low energy QCD model [3]. On the other hand, IB is studied for the QED correction of the K^0_{e3} decays [4].

A powerful way to express the K-π current is the chiral perturbation theory (ChPT) [5, 6]. ChPT has been developed based on the chiral symmetry which QCD intrinsically has, and it can be applied to all K^0_{e3} modes, including K_{e3ee}. Therefore, in this letter, we evaluate ChPT calculated to the next to leading order, expanded to the fourth power of the momentum of chiral field p [NLO(p^4)].

We searched for K_{e3ee} decay events in the K_L decay data of KTeV E799-II which was a fixed target experiment at Fermi National Accelerator Laboratory. An 800 GeV/c proton beam from Tevatron striking a BeO target was used to produce two parallel K_L beams. The vacuum decay region was allocated from 95 m to 159 m downstream from the target. Following a thin vacuum window at the end of decay region was a drift chamber spectrometer. The spectrometer had two pairs of drift chambers separated by an analysis magnet providing a transverse momentum kick of 0.2 GeV/c. A set of transition radiation detectors (TRD) behind the spectrometer was used for π-e rejection. Farther downstream, there were a trigger hodoscope, a pure CsI electromagnetic calorimeter, and a muon system. Photon vetoes were positioned around the vacuum decay region, the spectrometer and the calorimeter, vetoing particles escaping these detectors. We analyzed data acquired in the beginning of 1997. A detailed description for this experiment and analysis can be found in Ref. [7, 8].

The reconstruction of the events began with the identification of four charged tracks coming from a vertex in the decay region. The charged tracks were required to be identified as a set of $\pi^\pm e^\mp e^+ e^-$ using E/p, the energy reconstructed in the CsI calorimeter divided by the momentum measured in the spectrometer. For tracks identified as an electron by E/p, TRD was used to further identify electrons. The cut on TRD accepted 96.4% of electrons and rejected 93.7% of pions. Since the K_{e3ee} decay has three electrons, there are two candidates for a e^+e^- pair. In this letter, we define the pair which has smaller invariant mass as the "e^+e^- pair", and call the remaining electron as "$e^\pm_{ke3}$". Each electron momentum in the e^+e^- pair was required to be larger than 3 GeV/c. For the effective pion-muon separation by the muon filter, the pion momentum was required to be larger than 10 GeV/c. There is a two-fold ambiguity for the parent kaon energy, because a neutrino is not observed. The higher kaon energy solution [E_K(max)] was required to be lower than 200 GeV.

The Monte Carlo simulations (MC) were used to understand the acceptance of the signal mode, background modes, and a normalization mode. For the K_{e3ee} mode, we used ChPT[NLO(p^4)]. The absolute square of the matrix element of K_{e3ee} with ChPT[NLO(p^4)] was calculated by Tsuji *et al.* [9]. Bremsstrahlung photons from four charged particles in K_{e3ee} were added with the PHOTOS program [10, 11].

The major background for the K_{e3ee} mode was $K_L \to \pi^+\pi^-\pi^0_D$, where π^0_D denotes the $\pi^0 \to e^+e^-\gamma$ decay. MC study showed that 42% of them were caused by one of the pions being misidentified as an electron. The rest was caused by a photon converted into a e^+e^- pair and missing a pion and an electron. To reduce these $K_L \to \pi^+\pi^-\pi^0_D$ events accompanied by photon conversion, the $e^\pm_{ke3}$ momentum was required to be larger than 10 GeV/c. After E/p and TRD requirements, the number of $K_L \to \pi^+\pi^-\pi^0_D$ background events was 9.9% of the number of signal candidates. We applied one more constraint to suppress the $K_L \to \pi^+\pi^-\pi^0_D$ background using a kinematical variable,

$$k_{+-0} = \frac{(M_K^2 - M_{\pi e_{ke3}}^2 - M_{\pi^0}^2)^2 - 4M_{\pi e_{ke3}}^2 M_{\pi^0}^2 - 4M_K^2 p_t^2}{4(M_{\pi e_{ke3}}^2 + p_t^2)}, \quad (1)$$

where M_K and M_{π^0} are the kaon and π^0 masses, respectively. $M_{\pi e_{ke3}}$ is the invariant mass of $\pi^{\pm}$ and $e^{\mp}_{ke3}$ while the charged pion mass is assigned to $e^{\mp}_{ke3}$. The p_t is the transverse momentum of the $\pi^{\pm}e^{\mp}_{ke3}$ system. For the $K_L \to \pi^+\pi^-\pi^0$ decays, k_{+-0} is the squared longitudinal momentum of the π^0 in the frame in which the momentum of $\pi^+\pi^-$ system is transverse to the K_L direction, so that k_{+-0} should be larger than zero, as shown in Fig. 1. On the other hand, for K_{e3ee} events, k_{+-0} tends to have an unphysical value (k_{+-0}< 0). Requiring $k_{+-0} < -0.002$ GeV$^2/c^2$ rejected 80% of $K_L \to \pi^+\pi^-\pi^0_D$ background events and kept 80% of signal events. Finally, with all the cuts, (1.73 ± 0.07)% of 20225 signal candidates was estimated as the $K_L \to \pi^+\pi^-\pi^0_D$ background. The background due to $K_L \to \pi^+\pi^-\pi^0$ followed by $\pi^0 \to e^+e^-e^+e^-$ ($K_L \to \pi^+\pi^-\pi^0_{4e}$) was also effectively rejected by the cuts on $e^{\pm}_{ke3}$ momentum and the k_{+-0}. After all the analysis cuts, the amount of $K_L \to \pi^+\pi^-\pi^0_{4e}$ background is (0.91 ± 0.04)% of signal events.

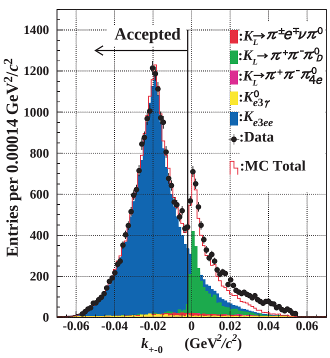

FIG. 1: The k_{+-0} distributions of data and MC's after all analysis requirements except for 'k_{+-0}'. The vertical line and arrow show the accepted region for the signal candidates (k_{+-0}< -0.002 GeV^2/c^2).

The $K_L \to \pi^{\pm}e^{\mp}\nu\pi^0$ decay followed by π^0_D (K_{e4D}) has the same set of charged particles as the signal. Without any special cuts for K_{e4D}, the number of K_{e4D} events is (1.59 ± 0.03)% of signal events. The radiative K^0_{e3} decay with an external conversion of the photon in the detector materials was rejected by requiring $M_{e^+e^-} > 5$ MeV/c^2. This background is (0.77 ± 0.09)% of signal events. Two K^0_{e3} decays in the same RF bucket with misidentifying a pion as an electron gives the same set of charged particles as K_{e3ee}. The estimated number of background events due to such events is 0.04% of signal events. The $\Xi \to \Lambda(\to p\pi^-)\pi^0_D$ decay can be a background source, when a proton is misidentified as a pion and a pion is misidentified as an electron. The estimated number of this background is 0.006% of signal events. The estimated total number of background events after all the cuts is 1019.2 ± 24.8, (5.04 ± 0.12)% of signal candidates.

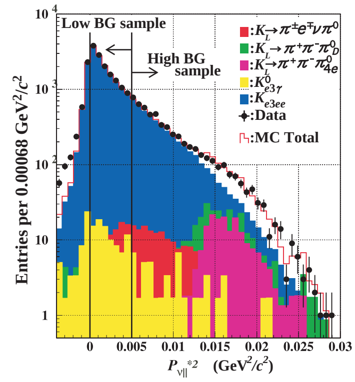

FIG. 2: The $P^{*2}_{\nu||}$ distribution of data and MC. The low background sub-sample and the high background sub-sample are separated by a vertical line on $P^{*2}_{\nu||}$= 0.005 GeV^2/c^2.

Figure 2 shows the distribution of the square of the longitudinal momentum of neutrino in the kaon rest frame ($P^{*2}_{\nu||}$), in which the K^0_{e3} decay modes have a characteristic shape. The data and MC of K_{e3ee} and backgrounds agree.

We used the $K_L \to \pi^+\pi^-\pi^0_D$ decay mode to normalize the number of K_L decays. The normalization mode events were collected with the same conditions as the signal mode analysis, except that the cut on k_{+-0} was reversed to k_{+-0}> -0.002 GeV$^2/c^2$. We ignored the photon in the decay to make the analysis conditions similar to those for the signal mode. Therefore, E_K has the two-fold ambiguity, and $E_K(\max) > 200$ GeV was required. The only significant background for the normalization analysis was the $K_L \to \pi^+\pi^-\pi^0$ decay followed by one of the photons from π^0 converted into an electron positron pair in the detector materials. The amount of this background was (0.558 ± 0.005)% of the normalization mode events.

The inefficiencies of electron in E/p and TRD cuts were larger for data analyses than MC, and inefficiency of pion in E/p was smaller for data analyses than MC. Because the numbers of electrons and pions are different between the signal mode and the normalization mode, the branching fraction of K_{e3ee} was multiplied by the factors $1 + \delta_i$, where $\delta_{e,E/p} = 3.4 \times 10^{-3}$, $\delta_{e,TRD} = 3.5 \times 10^{-3}$, and $\delta_{\pi,E/p} = 2.4 \times 10^{-3}$ for E/p cut and TRD cut for electron and E/p cut for pion, respectively. The ratio of the decay widths, $\mathcal{R}_{\frac{Ke3ee}{+-0D}}$, is

$$\frac{\Gamma(K_{e3ee}; M_{e^+e^-} > 5\text{MeV}/c^2, E^*_{e^+e^-} > 30\text{MeV})}{\Gamma(K_L \to \pi^+\pi^-\pi^0_D)} = [8.54 \pm 0.06(stat)] \times 10^{-3}, \quad (2)$$

where $E^*_{e^+e^-}$ is the energy of e^+e^- pair system in the kaon rest frame. The $E^*_{e^+e^-} > 30$ MeV roughly cor-

TABLE I: Systematic uncertainties in the K_{e3ee} branching fraction.

Source of uncertainty	Uncertainty on $B(K_{e3ee})(\%)$
External uncertainty	± 2.73
Unovserved photon in normalization analysis	± 1.03
Vertex χ^2 cut	± 0.7
Radiative corrections	± 0.51
Corrections for the π-e differences	± 0.46
E_K distribution	± 0.35
Cut-off on the $M_{e^+e^-}$	-0.18
Background estimations	± 0.05
MC statistics	± 0.32
Total of systematic uncertainties	± 3.21

responds to our sensitive region. To confirm our background estimation, we compared $\mathcal{R}_{\frac{Ke3ee}{+-0D}}$ between the signal regions $0 < P^{*2}_{\nu||} < 0.005$ GeV$^2/c^2$ and $P^{*2}_{\nu||} > 0.005$ GeV$^2/c^2$, in which the total background is 1.7% and 13.7% of the number of signal candidates, respectively. There was no significant difference in $\mathcal{R}_{\frac{Ke3ee}{+-0D}}$ between samples in two $P^{*2}_{\nu||}$ regions (1.6 σ). This fact assures the quality of the background estimations.

Table I lists the systematic errors in the determination of the $B(K_{e3ee})$. The largest systematic error is an external error from the branching fractions dominated by the error in $B(K_L \to \pi^+\pi^-\pi^0_D)$. The second largest systematic error is the uncertainty in the number of K_L decays. The number of K_L decays measured using the photon (full reconstruction measurement) was (0.88±0.51)% smaller than the analysis ignoring the photon. With this value and the systematic error in the full reconstruction measurement of $K_L \to \pi^+\pi^-\pi^0_D$, we assign 1.03% systematic error for the $B(K_{e3ee})$. The third largest systematic error is from the quality of the four track vertex "vertex χ^2" cut. The distribution of vertex χ^2 has a disagreement between data and MC, and its effect is not fully canceled by the normalization analysis. The next largest systematic error is from the radiative correction using the PHOTOS program. The signal acceptance increased by 3.6% if an inner bremsstrahlung was not generated in MC. We scaled this value by the difference of the number of observed $K_L \to \pi^\pm e^\mp \overset{(-)}{\nu} e^+e^-\gamma$ events between data and MC, $(6 \pm 8)\%$, and obtained $\pm 0.51\%$ as the error of the $B(K_{e3ee})$. Another error comes from the uncertainty in probabilities of missing π track due to hadronic interactions in TRD, ±0.45%, as was estimated using the GEANT program [14]. We also estimated the uncertainties in the inefficiencies of pion and electron in E/p selection and TRD selection. For the pion inefficiency study, the $\pi^\pm$ track sample was collected in the $K_L \to \pi^+\pi^-\pi^0_{\gamma\gamma}$ events identified with invariant mass restriction without E/p. The electron track sample was collected to study E/p (TRD) selection, in the $K_L \to \pi^+\pi^-\pi^0_D$ events identified with loose E/p (TRD) cut, strict TRD (E/p) cut, and strict invariant mass cuts on $M_{\pi\pi ee\gamma}$ and $M_{ee\gamma}$. Total error of these uncertainties for π-e differences was ±0.46%.

The branching fraction of K_{e3ee} with statistical and systematic uncertainty using the brancing fraction of $K_L \to \pi^+\pi^-\pi^0$ by KTeV [12] and $\pi^0 \to e^+e^-\gamma$ [13] is

$$B(K_{e3ee}; M_{e^+e^-} > 5\text{MeV}/c^2, E^*_{e^+e^-} > 30\text{MeV}) = [1.281 \pm 0.010(stat) \pm 0.040(syst)] \times 10^{-5}. \quad (3)$$

Figure 3 shows the invariant mass of e^+e^- pair system. There is a discrepancy between the data and MC in the low mass region. To study the effect of this discrepancy on the $B(K_{e3ee})$, we divided the $M_{e^+e^-}$ range from 0.005GeV/c^2 to 0.14GeV/c^2 in ten regions. We used the acceptance in each sliced region and summed the partial $B(K_{e3ee})$. There was no significant difference between the two values of $B(K_{e3ee})$.

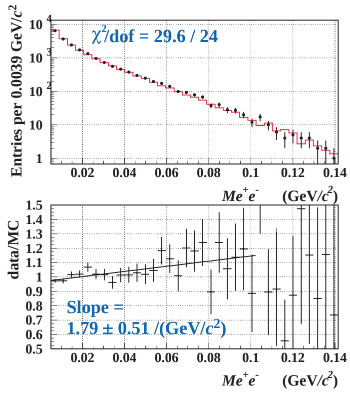

FIG. 3: Comparison of the $M_{e^+e^-}$ distribution for data (dots), and MC (histogram) with NLO(p^4) correction. The data-to-MC ratios shown below are fitted to a straight line. The slope of the fitted lines is (1.79 ± 0.51)/GeV/c^2.

Using the KTeV results for K^0_{e3} branching fraction [12], we determined

$$\mathcal{R}_{Ke3ee} \equiv \frac{\Gamma(K_{e3ee}; M_{e^+e^-} > 5\text{MeV}/c^2)}{\Gamma(K_{e3})} = (4.54 \pm 0.15) \times 10^{-3}. \quad (4)$$

The prediction for $\mathcal{R}_{ke3ee}$ is 4.06×10^{-5} by the leading order of ChPT, and 4.29×10^{-5} by the ChPT[NLO(p^4)]. The measured value is consistent with the value by ChPT[NLO(p^4)].

In the rest of this letter, we evaluate ChPT[NLO(p^4)] on the representation of the K-π structure. As the K-π form factor is extended by the square of the four momentum transfer to the leptons $t \equiv (p_K - p_\pi)^2$, higher order correction of ChPT is sensitive to t. However, the K_{e3ee} decay has a two-fold ambiguity in t due to the same reason as for E_K. To avoid this problem, we define the square of the transverse momentum transfer,

$$t_\perp = M_K^2 + M_\pi^2 - 2M_K\sqrt{p^2_{\perp,\pi} + M_\pi^2}, \quad (5)$$

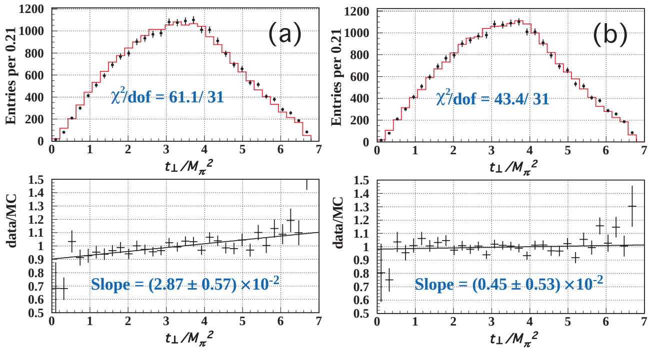

FIG. 4: Comparisons of the $t_\perp/M_\pi^2$ distributions for data (dots) and MC (histogram), (a) with MC-LO and (b) with MC-NLO(p^4). The data-to-MC ratios at the bottom are fit to a straight line.

where M_π is the charged pion mass and $p_{\perp,\pi}$ is the transverse pion momentum. Figure 4 shows that the $t_\perp/M^2$ distribution for data agrees with the NLO(p^4) correction, but not with the leading order of ChPT.

We also compared the invariant mass distributions between data and MC using ChPT[NLO(p^4)] for $M_{\pi eee}, M_{eee}, M_{\pi e}$ and $M_{e^+e^-}$. The reduced χ^2 of fitting of ChPT[NLO(p^4)] predictions to data for these invariant masses are 1.2-1.4. The slopes of the linear lines fitted to the data-to-MC ratios are zero within the statistical error, except for the distribution of $M_{e^+e^-}$. The slopes for the distribution of $M_{e^+e^-}$ in the region less than 0.1 GeV/c^2 is $(1.79\pm0.51)/(\text{GeV/c}^2)$. There is no such slope for the $M_{e^+e^-}$ distribution of the $K_L \to \pi^+\pi^-\pi^0_D$ decay [7].

In summary, KTeV determined the branching fraction of new neutral kaon decay mode, $B(K_{e3ee}; M_{e^+e^-} > 5\text{MeV}/c^2, E^*_{e^+e^-} > 30\text{MeV}) = [1.281 \pm 0.010(stat) \pm 0.040(syst)] \times 10^{-5}$. The measured branching fraction and the kinematical distributions agreed with the prediction by ChPT corrected to NLO(p^4), while disagreed with leading order of ChPT *i.e.* using point like K-π current. These facts indicate that ChPT[NLO(p^4)] expresses the K-π structure of this new semileptonic K decay as well as the other semileptonic K decays. The only remaining discrepancy between the data and MC[NLO(p^4)] is the $M_{e^+e^-}$ distribution. Further theoretical and experimental studies are required on $M_{e^+e^-}$ distribution.

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