CP Violation Results from KTeV

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Abstract: CP violation results from neutral kaon decays collected in 1996 and 1997 by the KTeV experiment are presented. We report a clear observation of direct CP violation in $K \to \pi\pi$ decays. In addition, we present results of searches for the CP violating rare decay modes $K_L \to \pi^o \nu\bar{\nu}$, $K_L \to \pi^o e^+ e^-$, and $K_L \to \pi^o \mu^+ \mu^-$. Finally, we discuss the first observation of an indirect CP violating angular asymmetry in the rare decay mode $K_L \to \pi^+\pi^- e^+ e^-$.

1. Introduction

The KTeV fixed target experiment at Fermilab consists of two experimental programs, E832 and E799II, designed mainly to search for direct CP violation in the neutral kaon system.

In the neutral kaon system, the strangeness states $(K^0, \bar{K^0})$ mix to produce the short and long lived kaons (K_S, K_L). CP violation is known to occur in this system due to a tiny asymmetry (parametrized by ϵ) in $K^0 \leftrightarrow \bar{K^0}$ mixing which gives rise to a small admixture of the wrong CP eigenstate in the (K_S, K_L) states. The Standard Model can accomodate CP violation in a natural way with a complex phase in the CKM quark mixing matrix. This model also allows for a second process, called "direct" CP violation and parametrized by ϵ', to occur in the decay amplitude itself.

The E832 experiment exploits the fact that direct CP violation would contribute differently to the rates of $K_L \to \pi^+\pi^-$ versus $K_L \to \pi^o\pi^o$ decays and thus would be observable as a nonzero value of $Re(\epsilon'/\epsilon) \approx$

$$\frac{1}{6}\left[\frac{N(K_L \to \pi^+\pi^-)/N(K_S \to \pi^+\pi^-)}{N(K_L \to \pi^o\pi^o)/N(K_S \to \pi^o\pi^o)} - 1\right]$$

Recent standard-model calculations predict a value for $Re(\epsilon'/\epsilon)$ in the range 10^{-4} to 10^{-3} [1, 2, 3], whereas a "superweak" interaction gives $Re(\epsilon'/\epsilon) = 0$. Prior to 1996, the most recent measurements of $Re(\epsilon'/\epsilon)$ were in nominal disagreement. The Fermilab E731 experiment measured $Re(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4}$ [4] while the CERN NA31 experiment measured $Re(\epsilon'/\epsilon) = (23.0 \pm 6.5) \times 10^{-4}$ [5]. E832 is one of a new generation of experiments designed to help resolve this discrepancy by measuring $Re(\epsilon'/\epsilon)$ with a precision of $\sim 1 \times 10^{-4}$.

The E799II experiment searches for direct CP violation through the rare decay processes $K_L \to \pi^o \nu\bar{\nu}$, $K_L \to \pi^o e^+ e^-$, and $K_L \to \pi^o \mu^+ \mu^-$. The former is expected to be mostly direct CP-violating, while the latter two are expected to have both CP-conserving and CP-violating contributions.

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2. The KTeV Detector

E832 measures all four $K_{L,S} \to \pi\pi$ decay modes simultaneously in order to reduce systematics due to time variations in beam characteristics and detector performance. The detector is shown in Figure 1. Two identical K_L beams enter the fiducial region 110 meters from the primary production target. The K_S beam is made by sending one of the K_L beams into a fully active regenerator made of plastic scintillator. To reduce acceptance biases, the regenerator moves between the two beams once per minute. The charged mode decays are measured with a charged spectrometer consisting of four drift chambers and an analysis magnet. The neutral mode decays are measured

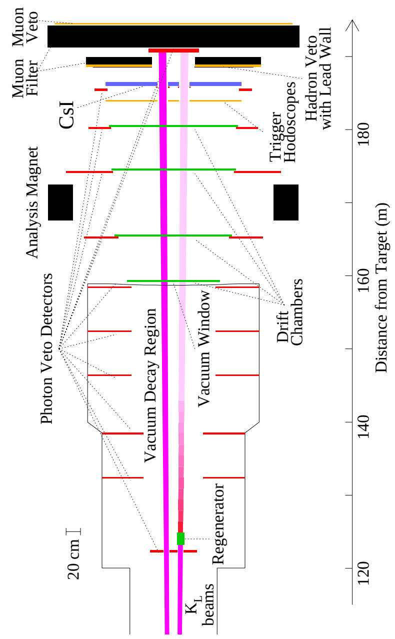

Figure 1: Plan view of the KTeV detector.

with a CsI electromagnetic calorimeter. A series of photon veto scintillation counters are used to detect photons escaping the fiducial volume.

For E799II the regenerator and the photon veto detector upstream of it are removed. To improve the π/e rejection, a necessity for rare kaon decay measurements, eight planes of transition radiation detectors are placed directly after the most downstream drift chamber.

3. The $Re(\epsilon'/\epsilon)$ Measurement

The results presented here are obtained from 2.3×10^6 $K \to \pi^0\pi^0$ decays recorded in our 8 week 1996 run. Due to a systematic problem in the charged data discovered in the 1996 data taking, we take the $K \to \pi^+\pi^-$ sample of 7.1×10^6 events from the first 18 days of our 1997 run. These samples represent about 23% of the data we acquired in 1996 and 1997. Since most systematics cancel in the single ratios, the only concern with using neutral and charged data from different running periods is whether or not the K_S/K_L flux is the same in the two periods, which we ensured by keeping the same beam absorbers and regenerator throughtout the run.

$K \to \pi^+\pi^-$ decays are reconstructed from two tracks, forming a vertex in both the horizontal and vertical views. The charged kaon mass resolution is approximately 1.6 MeV/c^2. In addition to other cuts, we require the two-track invariant mass to be within 10 MeV/c^2 of the known kaon mass and the square of the transverse momentum of the kaon to be less than 250 $(\text{MeV/c})^2$. After all cuts, the level of the remaining backgrounds is $\simeq 0.1\%$ and is dominated by $K_L \to \pi\mu\nu$ and $K_L \to \pi e\nu$ decays in the vacuum beam and by non-coherent K_S regeneration in the regenerator beam. The background level is understood to 10% of itself.

$K \to \pi^o\pi^o$ events are reconstructed from four energy clusters in the CsI calorimeter. There are three possible ways to combine four clusters, and we choose the combination in which the reconstructed vertex of the two π^o's are the closest. The mass resolution of the neutral kaon events is about 1.5 MeV/c^2. In addition to other cuts, we require the four-photon invariant mass to be within approximately 8 MeV/c^2 of the known kaon mass, and the transverse energy-weighted position of the four photons to be near one of the two beam holes. After all cuts, the most important remaining backgrounds are $K_L \to 3\pi^0$ with fused or missing photons, and K_S produced noncoherently in the regenerator. The background level is $\simeq 1\%$ and is understood to 10% of itself.

After background subtraction, the net yields are 2,607,274 $\pi^+\pi^-$ in the vacuum beam, 4,515,928 $\pi^+\pi^-$ in the regenerator beam, 826,254 $\pi^o\pi^o$ in the vacuum beam, and 1,433,923 $\pi^o\pi^o$ in the regenerator beam.

The principal difference between the K_L and K_S data samples is in the decay vertex distributions shown in Figure 2 as a function of Z, the distance from the kaon production target. The $Re(\epsilon'/\epsilon)$ measurement therefore requires a precise understanding of the Z-dependence of the detector acceptance.

To correct for the large difference in acceptance between K_L and K_S decays, we rely on a detailed Monte Carlo. Figure 3 shows the comparison of the decay vertices for various charged and neutral decays. In the case of $K_L \to \pi^+\pi^-$, the ratio of the data/Monte Carlo exhibits a $\sim 3\sigma$ slope. We see no such slope in the higher

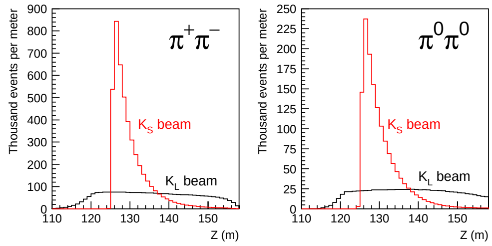

Figure 2: Decay distributions for $K \to \pi^+\pi^-$ and $K \to \pi^o\pi^o$ decays.

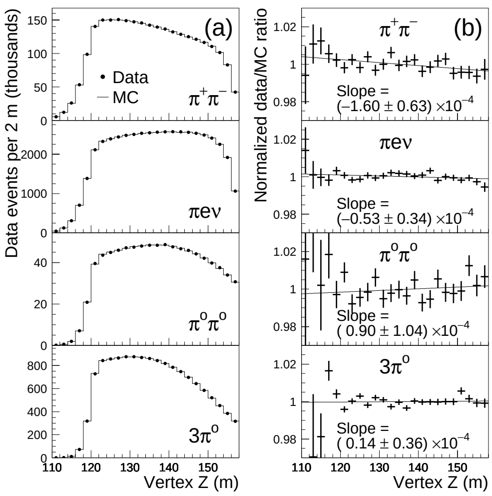

Figure 3: (a) Data versus Monte Carlo comparisons of vacuum-beam Z distributions for different decay modes. (b) Linear fits to the data/MC ratio of Z distributions.

statistics $K \to \pi e \nu$ comparison nor in any of the neutral mode comparisons. We use the slope in the $K_L \to \pi^+\pi^-$ comparison to assign a systematic error for the detector acceptance, our largest source of systematic error. Other sources of systematic error include the calorimeter energy scale and linearity, backgrounds, analysis cuts and uncertainties in physics parameters. The total systematic error is 2.8×10^{-4}.

Since the regenerator beam contains a significant K_L component as well as an interference term between the K_S and K_L amplitudes, we determine $Re(\epsilon'/\epsilon)$ not by taking the simple double ratio, but by fitting the number of decays in each of the four modes as a function of the kaon energy. In our fit, there were 48 fit bins (12x10 GeV energy bins for each of the four decay modes) and 27 floating parameters (2 regeneration, 24 kaon flux normalizations, and $Re(\epsilon'/\epsilon)$). Physics parameters such as Δm and τ_S were fixed to the PDG 1998 values. Fitting was done "blind", by hiding the value of $Re(\epsilon'/\epsilon)$ with an unknown offset, until after the analysis and systematic error evaluations were finalized.

The result is $Re(\epsilon'/\epsilon) = (28.0 \pm 3.0(stat) \pm 2.8(syst)) \times 10^{-4}$ [6]. Recently, the NA48 experiment obtained two new results: $Re(\epsilon'/\epsilon) = (18.5 \pm 7.3) \times 10^{-4}$ based on their 1997 data, and a preliminary result of $Re(\epsilon'/\epsilon) = 12.2 \pm 4.9$ based on their 1998 data.

4. Searches for $K_L \to \pi^o l \bar{l}$

All analyses which are described below with the exception of the $K_L \to \pi^o \nu \bar{\nu}$ ($\pi^o \to \gamma\gamma$) are based on the 1997 E799II data set which contained 2.7×10^{11} K_L decays. The $K_L \to \pi^o \nu \bar{\nu}$ ($\pi^o \to \gamma\gamma$) analysis used a special one day run which corresponded to 6.8×10^7 K_L decays.

Theoretical predictions [7, 8] for the direct and indirect CP-violating components as well as the CP-conserving part of the $K_L \to \pi^o l \bar{l}$ branching ratios are listed in Table 1

4.1 $K_L \to \pi^o \nu \bar{\nu}$

The $K_L \to \pi^o \nu \bar{\nu}$ decay is predominantly direct CP-violating with a branching ratio given by

$$B(K_L \to \pi^o \nu \bar{\nu})_{DIR} = \left(\frac{m_t}{m_W}\right)^{2.2} A^4 \eta^2 \sim 3 \times 10^{-11}$$

where the CKM parameter η governs CP violation and represents the height of the unitarity triangle.

For the decay $K_L \to \pi^o \nu \bar{\nu}$ we have made two searches using two different techniques. The first method used the decay $\pi^o \to \gamma\gamma$ and the second method used the Dalitz decay $\pi^o \to e^+e^-\gamma$. The advantage of the first method is that the branching ratio into two photons is 80 times larger and the acceptance is several times larger than that for the Dalitz decay. The advantage of the second method is that the charged vertex information helps to reduce backgrounds. The $\pi^o \to \gamma\gamma$ method resulted in one candidate which was consistent with the expected background and gave a 90% confidence upper limit on the branching ratio of 1.6×10^{-6} [9]. The $\pi^o \to e^+e^-\gamma$ method

Decay mode	Direct CPV	Indirect CPV	CP Conserving
$K_L \to \pi^o \nu\bar{\nu}$	3×10^{-11}	$\sim 10^{-15}$	$\sim 2 \times 10^{-15}$
$K_L \to \pi^o e^+e^-$	5×10^{-12}	$1 - 5 \times 10^{-12}$	$1 - 2 \times 10^{-12}$
$K_L \to \pi^o \mu^+\mu^-$	1×10^{-12}		$0.5 - 10 \times 10^-12$

Table 1: Branching ratios for $K_L \to \pi^o l\bar{l}$

resulted in no candidates and a 90% confidence upper limit of 5.9×10^{-7} [10], a factor of 100 improvement over the previous limit. It should be noted that the $\pi^o \to e^+e^-\gamma$ method required 50 times more K_L flux than the $\pi^o \to \gamma\gamma$ method, yet it only improved the upper limit by a factor of three. Currently, there are two new proposals, one at Fermilab and one at Brookhaven, to measure η to 10% using the latter method.

4.2 $K_L \to \pi^o e^+e^-$

Although the decay $K_L \to \pi^o e^+e^-$ 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 the CP-conserving amplitudes are comparable in size to the direct CP-violating contribution and must be understood before the direct CP-violating component can be determined.

The CP-conserving amplitude can be estimated from theory and from a measurement of the CP-conserving related decay $K_L \to \pi^o\gamma\gamma$. During E832 running, KTeV accumulated a sample of $K_L \to \pi^o\gamma\gamma$ events from which we extract a CP-conserving contribution of $(1 - 2) \times 10^{-12}$ to the $K_L \to \pi^o e^+e^-$ branching ratio.

The background limiting mode to the decay $K_L \to \pi^o e^+e^-$ comes from the radiative Dalitz decay, $K_L \to e^+e^-\gamma\gamma$. KTeV has a sample of 1988 of these events with an estimated background of 76.6 ± 3.3 events. With a photon energy cutoff of 5 GeV, the preliminary measurement of the branching ratio is $(6.31 \pm 0.14(stat) \pm 0.43(syst)) \times 10^{-7}$, roughly an order of magnitude improvement over the previous measurement.

After all cuts, a Monte Carlo background estimate predicts 1.06 ± 0.41 events in the signal region from $K_L \to e^+e^-\gamma\gamma$, the only remaining background. There are 2 events observed in the signal region and we quote a 90% upper limit for the branching ratio of 5.1×10^{-10} [11], roughly an order of magnitude improvement over the previous limit.

4.3 $K_L \to \pi^o \mu^+\mu^-$

Like the electron mode, the decay $K_L \to \pi^o\mu^+\mu^-$ is a probe of direct CP violation, although the direct CP-violating component is small relative to the CP-conserving component. It also has a potential background from $K_L \to \mu^+\mu^-\gamma\gamma$, which has a branching ratio calculated to be $(9.1 \pm 0.8) \times 10^{-9}$ but has not previously been observed.

We report here on a first observation of the decay $K_L \to \mu^+\mu^-\gamma\gamma$. Four events above a background of 0.155 ± 0.081 events are observed. The measured branching ratio, with a $M\gamma\gamma$ cutoff of $1MeV/c^2$, is $(10.4^{+7.5}_{-0.81}(stat) \pm 0.14(syst)) \times 10^{-9}$, consistent with theoretical prediction.

After all cuts, the most significant single background to $K_L \to \pi^o\mu^+\mu^-$ comes from $K_L \to \mu^+\mu^-\gamma\gamma$ and is estimated to be 0.343 ± 0.048 events in the signal region. Other backgrounds come from pion punch-through and decay-in-flight from $K_L \to \pi^+\pi^-\pi^o$, and from $K_L\pi^\pm\mu^\mp\bar{\nu}$ decay with 2 accidental photons. The total background contribution is expected to be 0.87 ± 0.15 events. There are 2 events in the signal region and we set a 90% upper limit on the branching ratio of 3.8×10^{-10} [12], which is an order of magnitude improvement over the previous limit.

5. CP Violation in $K_L \to \pi^+\pi^-e^+e^-$

The decay $K_L \to \pi^+\pi^-\gamma$ has both a CP-conserving direct emission M1 amplitude and a CP-violating inner bremsstrahlung (IB) amplitude. The interference between these two amplitudes results in a CP-violating polarization that can be measured if the photon converts to an e^+e^- pair. The decay $K_L \to \pi^+\pi^-e^+e^-$ internally converts the photon and thus provides another opportunity to observe indirect CP violation.

Indirect CP violation in $K_L \to \pi^+\pi^-e^+e^-$ is expected to cause an asymmetry in the angle ϕ between the $\pi^+\pi^-$ and e^+e^- decay planes:

$$A_\phi \equiv \frac{N_{\sin_\phi \cos_\phi} > 0 - N_{\sin\ _\phi \cos_\phi} < 0}{N_{\sin_\phi \cos_\phi} > 0 + N_{\mathrm{si\ n}_\phi \cos_\phi} < 0}$$

Earlier, based on 2% of the data, we reported the first observation of this decay and measured a branching ratio of $(3.2 \pm 0.6(stat) \pm 0.4(syst)) \times 10^{-7}$ [13] More recently, using the complete 1997 data set, we reported a preliminary branching ratio of $(3.63 \pm 0.11(stat) \pm 0.14(syst)) \times 10^{-7}$.

The analysis of the CP-violating asymmetry was done using the full data set. After all cuts, 1811 $K_L \to \pi^+\pi^-e^+e^-$ events were obtained above a background of 45 ± 11 events. The background is dominated by $K_L \to \pi^+\pi^-\pi^o_D$ events where π^o_D was a Dalitz decay, $\pi^o \to e^+e^-\gamma$.

The observed asymmetry shown in Figure 4 was $23.3 \pm 2.3(stat)\%$ before corrections. Correcting for acceptance yields a value for the asymmetry of $(13.5 \pm 2.5(stat) \pm 1.2(syst))\%$ [14]. This is in good agreement with the theoretical prediction of $\simeq 14\%$ [15].

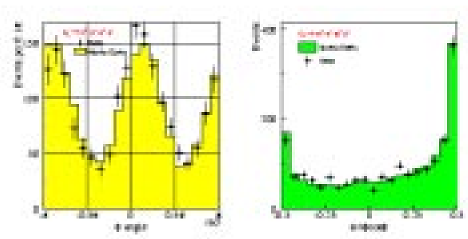

Figure 4: (a) Observed ϕ and (b) $\sin\phi\cos\phi$ distributions. The dots are data and the histogram is MC.

Possible sources of false asymmetry were considered, including backgrounds and detector acceptance. To check for detector asymmetries, the asymmetry was calculated for a sample of approximately five million $K_L \to \pi^+\pi^-\pi^o_D$ decays. In this sample, an asymmetry of $-0.02 \pm 0.05\%$ was observed.

6. Conclusions

KTeV has measured $Re(\epsilon'/\epsilon)$ to be $(28.0 \pm 3.0(stat) \pm 2.8(syst) \times 10^{-4}$ based on 23% of the data collected in 1996 and 1997. This result clearly indicates the existence of direct CP violation. In 1999, we collected a $K \to \pi\pi$ sample of comparable statistics to the whole 1996-1997 data set. With the combined statistics of the total data set, we expect to be able to achieve an error on $Re(\epsilon'/\epsilon)$ of $\sim 1 \times 10^{-4}$.

KTeV has improved the upper limits for the branching ratios of the direct CP-violating decays $K_L \to \pi^o\nu\bar{\nu}$, $K_L \to \pi^o e^+e^-$, and $K_L \to \pi^o\mu^+\mu^-$ by approximately an order of magnitude in each case. KTeV has also made the first observation of the rare decay $K_L \to \pi^+\pi^-e^+e^-$ and measured an indirect CP-violating angular asymmetry in this decay. In 1999, we approximately tripled the statistics of the 1996-1997 rare decay data set, extending the reach of the $K_L \to \pi^o l\bar{l}$ searches into regions where possible enhancements from SUSY contributions are expected.

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