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Y.B. Hsiung
For the KTeV Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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An Observation Of Direct-CP Violation - ϵ'/ϵ Result From KTeV

Yee Bob Hsiung[a]*

[a]MS122, Fermilab, P. O. Box 500, Batavia, IL 60510

We report the first KTeV measurement for the search of direct-CP violation by using 23% of the data sample collected in the 1996-97 fixed target run at Fermilab, . The result is, $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$, nearly 7σ above zero obtained by a blind analysis. This firmly establishes the long-sought "direct-CP violation" effect in the two-pion system ($\pi^+\pi^-$ versus $\pi^0\pi^0$) of neutral kaon decays. Other new measurements of Δm, τ_S, $\Delta\phi$ and a limit on the diurnal variation of ϕ_{+-} for testing CPT invariance from the same data sample are also presented.

1. Introduction

One long lasting piece of puzzle in particle physics is the origin of CP violation, where C stands for the charge conjugation (exchange particle and anti-particle) and P stands for the parity (space inversion). Thirty-five years after the first unexpected discovery [1] of CP violation in $K_L \to \pi\pi$ decays in 1964, we can only explain the dominant effect as due to a small asymmetry of the $K^0 - \bar{K^0}$ mixing or admixture of wrong CP states in the K_S and K_L neutral kaons, parametrized by ϵ (about 0.0023). The question is "Does CP violation also occur in the $K \to \pi\pi$ decay process itself?" or "Can CP-odd component of neutral kaon decay directly into CP-even final states?" An effect referred as "direct-CP violation" [2], parametrized by ϵ' which contributes differently to the rates of $K_L \to \pi^+\pi^-$versus $K_L \to \pi^0\pi^0$ decays (relative to the corresponding K_S decays), and would be observed as a nonzero value in the ratio of $\mathrm{Re}(\epsilon'/\epsilon)$.

Experimentally we measure the double ratio R,

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} = \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} \approx 1 + 6\mathrm{Re}(\epsilon'/\epsilon). \quad (1)$$

The standard Cabbibo-Kobayashi-Maskawa (CKM) model [3] accomodates CP violation with a complex phase in the quark mixing matrix, but the calculations of $\mathrm{Re}(\epsilon'/\epsilon)$ are still uncertain depending on several input parameters and on the method used to estimate the hadronic matrix elements. Most recent estimates [4][5] had given non-zero values slightly below 10^{-3}; however, another group [6] gave a somewhat larger estimates. Alternatively, a "superweak" interaction [7] could also produce the observed CP-violating mixing effect (ϵ) but would give $\epsilon'/\epsilon = 0$. Therefore, a non-zero measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ would rule out the possibility that a superweak interaction is the sole source of CP violation, and would establish the "direct" CP violation from the decay process itself.

The earlier two measurements of $\mathrm{Re}(\epsilon'/\epsilon)$ from Fermilab-E731 [8] and CERN-NA31 [9] were

$$\mathrm{Re}(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4}, \quad (E731) \quad (2)$$
$$\mathrm{Re}(\epsilon'/\epsilon) = (23.0 \pm 6.5) \times 10^{-4}, \quad (NA31) \quad (3)$$

and the PDG average was $(15 \pm 8) \times 10^{-4}$ [10] which gave inconclusive interpretations between standard model or superweak CP-violation. New experiments have been constructed at Fermilab(KTeV), CERN(NA48) [11] and Frascati(KLOE) to measure $\mathrm{Re}(\epsilon'/\epsilon)$ with a precision of $\sim 1 \times 10^{-4}$ for the search of "direct" CP violating effect and determining its magnitude.

We report here a new measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ from 23% of the data collected by the KTeV experiment (E832 run period) during 1996-97 fixed target run at Fermilab. This result has recently been published in [12] after the first preliminary announcement in February 24, 1999.

*for KTeV Collaboration: Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia and Wisconsin.

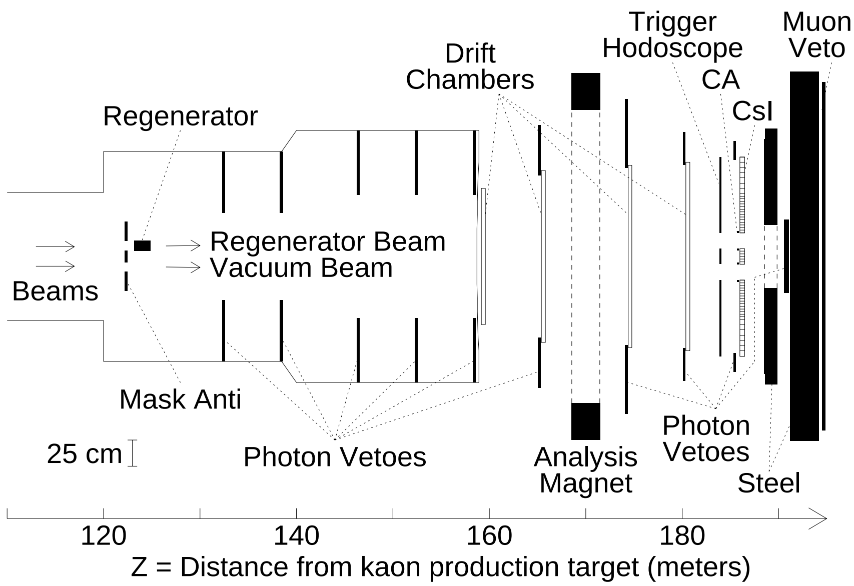

Figure 1. Plan view of the KTeV apparatus with double kaon beam as configured to measure $\mathrm{Re}(\epsilon'/\epsilon)$. The evacuated decay volume ends with a thin vacuum window at $Z = 159\ m$, followed by magnetic spectrometer for $\pi^+\pi^-$. The label "CsI" indicates the electromagnetic calorimeter for $\pi^0\pi^0$ detection.

2. KTeV and Double Beam Method

The KTeV experiment was designed to improve on the previous experiments and ultimately to have the sensitivity to establish direct CP violation if $\mathrm{Re}(\epsilon'/\epsilon)$ is on the order of 10^{-3}. The experimental technique is the same as in E731 [13] with many improvements in beam and detector. Double kaon beams from a single BeO target is used to enable the simultaneous collection of K_L and K_S decays to minimize the systematics due to time variation of beam flux and detector inefficiencies. A precision magnetic spectrometer is used to minimize backgrounds in the $\pi^+\pi^-$ samples and to allow *in situ* calibration of the calorimeter with electrons. A high precision electromagnetic calorimeter, Cesium Iodide (CsI) array, is used for $\pi^0\pi^0$ reconstruction and better background suppression. Nearly hermetic photon vetoes (up to 100 $m$rad) are used for further background reduction for $\pi^0\pi^0$ mode. A new beamline was constructed for KTeV with cleaner beam collimation and improved muon sweeping to minimize the accidental background rate in the detector. While the method of producing a K_S beam (by passing a K_L beam through a "regenerator") is also the same as E731, the KTeV regenerator is made of scintillator and is fully active to reduce the scattered background to the coherently regenerated K_S.

The KTeV detector is shown in Fig. 1. Two beams (called "regenerator" and "vacuum") enter the evacuated decay region, with the main detector elements located downstream. The regenerator switches sides once every accelerator cycle to minimize the effect of any left-right asymmetry of beam or detectors. A movable "shadow absorber" far upstream attenuates the kaon beam onto the regenerator. To measure the double ratio of decay rates for $\mathrm{Re}(\epsilon'/\epsilon)$, we need understand the difference between the acceptances for K_S versus K_L decays to each $\pi\pi$ final state. Event reconstruction and selection are done with identical criteria for decays in either beam, so the principle difference between the K_S and K_L data samples is in the decay vertex distributions, shown in Fig. 2 as

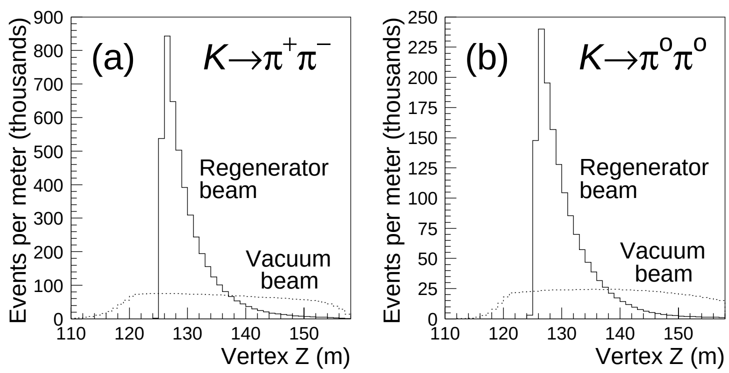

Figure 2. Decay vertex distributions for the (a) $K \to \pi^+\pi^-$ and (b) $K \to \pi^0\pi^0$ decay modes, showing the difference between the "regenerator" (K_S) and "vacuum" (K_L) beams.

a function of Z, the decay distance from the target. Therefore, the most crucial requirement of measuring Re(ϵ'/ϵ) with this technique is a precise understanding of the Z-dependence of the detector acceptance. The acceptance for decays upstream of $Z = 122\ m$ in the vacuum beam is defined by a lead-scintillator counter, "mask-anti" (MA), with two square holes 50% larger than the beams. In the regenerator beam, the beginning of the decay region is sharpely defined by a thin lead-scintillator module at the end of the 1.7 m long regenerator.

The momenta of charged particles from the decay are measured by the spectrometer consisting of four drift chambers, each with two horizontal and two vertical planes of sense wires, and a large dipole magnet with 412 MeV/c transverse kick. The position resolution is typically 110 μm for the chamber and the momentum resolution is 0.4% at the mean pion momentum of 36 GeV/c.

The electromagnetic calorimeter consists of 3100 blocks of pure CsI in a square array 1.9 m on a side and 50 cm deep. Two 15 cm square holes allow passage of the neutral beams through the calorimeter. The calorimeter was calibrated using 190 million momentum-analyzed electrons (and positrons) from $K_L \to \pi e \nu$ decays collected during the normal running. The average energy resolution for photons from $\pi^0\pi^0$ is 0.7% with a mean photon energy of 19 GeV.

The inner aperture at the CsI is defined by a tungsten-scintillator counter (CA) around each beam hole. In addition, there are ten lead-scintillator sandwiched (16 X_0) "photon veto" counters to detect particles escaping from the decay volume or missing the CsI, in order to suppress the major $K_L \to 3\pi^0$ background to the CP-violated $\pi^0\pi^0$ signal mode.

The charged mode (for $\pi^+\pi^-$, $Ke3$) trigger is based on a scintillator hodoscope located just upstream of CsI calorimeter and the requirements on the number and pattern of hits in the drift chambers. The neutral mode trigger is based on a fast energy sum from the calorimeter and a hardware cluster finding processor (e.g. for $\pi^0\pi^0$ it must find 4 or 5 clusters of energy in the CsI). Additional fast veto signals from regenerator, photon vetoes and a downstream muon veto hodoscope located behind 4 m of steel are also used in the trigger to keep the trigger rate at a manageable level. A CPU-based "Level 3 filter" reconstructs events on-line and applies loose kinematic cuts to select $\pi^+\pi^-$ and $\pi^0\pi^0$ candidates. Large samples of $K_L \to \pi e \nu$ and $K_L \to 3\pi^0$ decays are also recorded for detector calibration and acceptance studies. In addition, an "accidental" trigger is formed by using small scintillation counters near 90° to the target to randomly record the underlying activity in the KTeV detector with the same instantaneous rate as the physics data for study.

3. The Analysis of ϵ'/ϵ

The $\pi^0\pi^0$ samples in this analysis were collected in Nov.-Dec. 1996, while $\pi^+\pi^-$ samples were from the first 18 days of data in Apr.-Jul. 1997. The 1996 $\pi^+\pi^-$ samples are analyzed but not used for this result because of a large Level 3 tracking inefficiency (about 22% loss) from an unanticipated drift chamber effect which could sometimes delay a hit by 20 ns or more (due to lower gas gain and higher threshold relative to the first avalanche pulse in the chamber). The inefficiency was nearly the same for both beams but still would have led to a larger systematic error. The Level 3 software was modified for the 1997 run to allow for this effect, resulting in an inefficiency of less than 0.1% and reduced systematics. The construction of a double ratio (Eq. 1) allows us to use data from two different time periods with small systematics.

Event reconstruction and selection are done with identical cuts and criteria for decays in either beam to minimize the systematics. The $\pi^+\pi^-$ candidates are selected, by requiring each pion to have a momentum $p_\pi > 8\ GeV/c$ and to deposit less than 85% of its energy in the CsI calorimeter. Cuts are also made near the edges of the detectors, and on the separation between the two pions at the chambers and calorimeter to avoid poorly reconstructed event topology and to cleanly define the acceptance. The $\pi^+\pi^-$ invariant mass is required to be between 488 and 508 MeV/c^2 (where the mass resolution is about 1.6 MeV/c^2) and the square of the transverse momentum of the $\pi^+\pi^-$ system relative to the initial kaon trajectory from target, p_T^2, is required to be less than 250 MeV^2/c^2.

The $\pi^0\pi^0$ candidates are reconstructed from four-photon events by choosing the photon pairing combination consistent with two π^0 decays at a common kaon decay vertex. Each photon is required to have an energy $E_\gamma > 3\ GeV$ and to be at least 5 cm away from the outer edge of the CsI and 7.5 cm from any other photon. The $\pi^0\pi^0$ invariant mass is required to be between 490 and 505 MeV/c^2 (where the mass resolution is about 1.5 MeV/c^2). The initial kaon trajectory is not well known, so the only available indicator of kaon scattering is the position of the energy centroid of the four photons at the CsI. This is used to calculate a square box "ring number", defined as four times the square of the larger normal distance (either horizontal or vertical), in unit of cm, from the centroid to the center of the closer beam. The cut value is required to be less than 110, which selects events with energy centroid lying within a square region of area 110 cm^2 centered on each beam.

In both $\pi^+\pi^-$ and $\pi^0\pi^0$ analyses, cuts are made on energy deposits in the MA, photon veto counters and regenerator. The final samples consist of events with $110 < Z < 158\ m$ and $40 < E_K < 160\ GeV$.

Detailed Monte Carlo (MC) simulation is used to determine the detector acceptance and to evaluate backgrounds. The simulation models kaon production and regeneration to generate decays with the same energy E_K and decay vertex Z distributions as the data. The decay products are traced through the KTeV detector, allowing for electromagnetic interactions with detector material and pion decay. The acceptance is largely determined by the geometry of the detector and by geometric analysis cuts. Simulation of the detector response is also included to understand the reconstruction biases. High statistics $\pi e\nu$ and $3\pi^0$ data samples are collected to check or tune various aspects of the detector geometry and simulation. To reproduce the biases due to underlying activity in the detector, an event from the "accidental" trigger is overlaid on top of each simulated decay; the net effect on $\mathrm{Re}(\epsilon'/\epsilon)$ is $\sim 1 \times 10^{-4}$.

Backgrounds to the $\pi^+\pi^-$ samples are determined by using sidebands in the mass and p_T^2 distributions to normalize MC predictions from various background processes. Figure 3 (a) and (b) show that the p_T^2 distributions for data are well described by the sum of coherent $\pi\pi$ MC and total background MC. Semileptonic $K_L \to \pi e\nu$ and $K_L \to \pi\mu\nu$ decays, with the electron or muon misidentified as a pion, contribute 0.069% mainly to the vacuum beam. The dominant regenerator-beam background (0.072%) is from kaons which scatter in the regenerator before decaying to $\pi^+\pi^-$. Kaons which scatter in the fi-

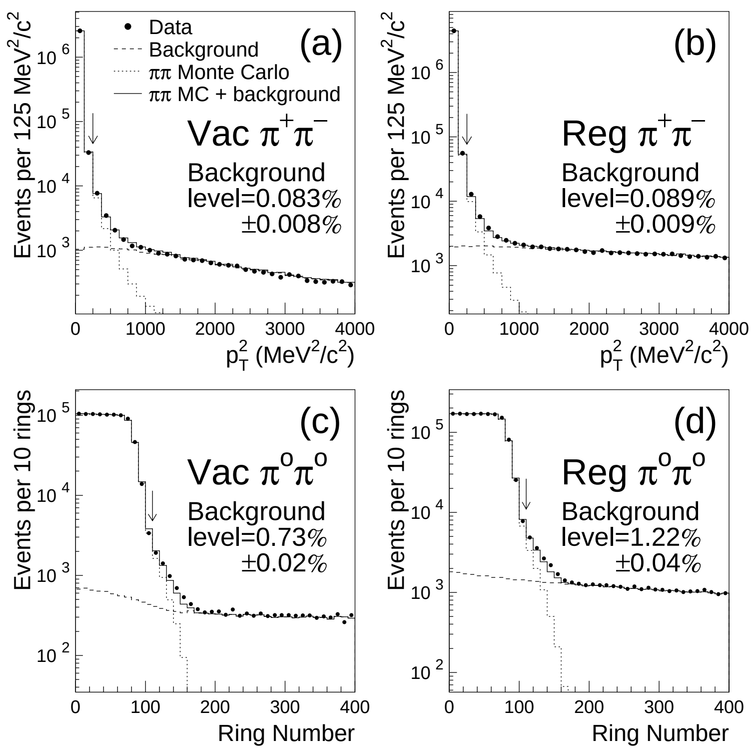

Figure 3. Distributions of p_T^2 for the $\pi^+\pi^-$ samples and ring number for the $\pi^0\pi^0$ samples. Total background levels and uncertainties (dominated by systematics) are given for the samples passing the analysis cuts (arrows).

nal beam-defining collimator contribute an additional 0.014% to each beam. Each type of scattering is parametrized using the $\pi^+\pi^-$ data of the same running period and incorporated into the MC simulation.

Background levels are larger for the $\pi^0\pi^0$ samples since the ring-number variable is not as effective as p_T^2 at identifying scattered kaons and detecting "crossover" scattering from the regenerator into the vacuum beam. Ring-number distributions are shown in Fig. 3 (c) and (d). The upturn under the peak in (c) is due to $K_L \to 3\pi^0$ decays with lost and/or overlapping photons; it is determined, using mass sidebands, to contribute a background of 0.27% mainly to the vacuum beam. Ring-number sidebands are used to normalize MC distributions from kaons that scatter in the regenerator or collimator before decaying to $\pi^0\pi^0$. The vacuum (regenerator) beam background includes 0.30% (1.07%) from regenerator scattering and 0.16% (0.14%) from collimator scattering.

After background subtraction, the net yields are 2.607M $\pi^+\pi^-$ events in the vacuum beam, 4.516M $\pi^+\pi^-$ in the regenerator beam, 862K $\pi^0\pi^0$ in the vacuum beam and 1.434M $\pi^0\pi^0$ in the regenerator beam.

4. ϵ'/ϵ Fits and Result

Re(ϵ'/ϵ) is extracted from the background-subtracted data using a fitting program which analytically calculates regeneration and decay distributions accounting for $K_S - K_L$ interference. After the acceptance correction, the resulting prediction for each decay mode is integrated over Z and compared to data in 10 GeV bins of kaon energy. CPT symmetry is assumed for this fit, and the values of $K_S - K_L$ mass difference (Δm) and K_S lifetime (τ_S) are fixed to PDG values [10]. The regeneration amplitude is allowed to float in the fit, but constrained to have a power law dependence on kaon energy, with the phase determined by analyticity [13][15]. The kaon energy distribution are also allowed to float for $\pi^+\pi^-$ and $\pi^0\pi^0$ modes in each energy bin (24 fit parameters in all).

Fitting was done "blind", by hiding the value of $\mathrm{Re}(\epsilon'/\epsilon)$ with an unknown offset between η_{+-} and η_{00}, until after the analysis and systematic error evaluation were finalized. The final fit result is $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 3.0) \times 10^{-4}$, where the error is statistical only with a $\chi^2/d.o.f = 30/21$.

5. Systematics and Checks

Only biases which affect the K_L and K_S samples differently will lead to systematic errors on $\mathrm{Re}(\epsilon'/\epsilon)$, a virtue of double ratio and double beam method. Possible sources are divided into four classes: (1) data collection inefficiencies; (2) biases in event reconstruction, sample selection, and background subtraction; (3) misunderstanding of the detector acceptance; and (4) uncertainties in kaon flux and physics parameters. Table 1 summarizes all of the estimated contributions and the detailed discussion on systematics can be found in [12].

The accuracy of the background determination for the $\pi^0\pi^0$ samples depends on our understanding of kaon scattering in the regenerator and collimator. We consider several variations in the procedure for determining the scattering distributions from the $K \to \pi^+\pi^-$ data; these affect the shapes of the background MC ring-number distributions, but the sideband normalization procedure limits the impact on $\mathrm{Re}(\epsilon'/\epsilon)$ ($\leq 0.8 \times 10^{-4}$).

A systematic shift in measured energy scales can shift the reconstructed Z vertex and E_K distributions for the $\pi^0\pi^0$ sample and thus can bias $\mathrm{Re}(\epsilon'/\epsilon)$, mainly by moving K_L events past the fiducial Z cut at 158 m. After calibrating the calorimeter with electrons (and allowing for a small expected electron-photon difference), a final energy scale correction for photons of -0.125% is determined by matching the sharp turn-on of the $\pi^0\pi^0$ Z distribution at the regenerator edge between data and MC. After making this correction, a check using π^0 pairs produced by hadronic interactions in the vacuum window reveals a Z mismatch of 2 cm at the downstream end of the decay region, leading to a systematic error of 0.7×10^{-4} on $\mathrm{Re}(\epsilon'/\epsilon)$. Residual nonlinearities in the calorimeter response contribute an additional error of 0.6×10^{-4}.

The largest systematics in Table 1 comes from the detector acceptance. Many potential detector modeling problems would affect the acceptance as a function of Z, so a crucial check of our understanding of the acceptance is to compare the Z distribution for the data against the MC simulation. Figure 4 shows the vacuum-beam comparisons for the $\pi^+\pi^-$ and $\pi^0\pi^0$ signal modes as well as for the two high statistics $\pi e \nu$ and $3\pi^0$ samples. The overall agreement is fairly good, but since the mean Z positions for K_L and K_S decays differ by about 6 m, a relative slope of 10^{-4} per meter in the data/MC ratio would cause an error of 10^{-4} on $\mathrm{Re}(\epsilon'/\epsilon)$. As shown in Fig. 4 (b), the $\pi e \nu$ comparison agrees to better than this level; however, the $\pi^+\pi^-$ comparison has a ($\sim 2.5\sigma$) slope of $(-1.60 \pm 0.63) \times 10^{-4}$ per meter. We assign a systematic error on $\mathrm{Re}(\epsilon'/\epsilon)$ based on the full size of the slope, 1.6×10^{-4}. The $3\pi^0$ and $\pi^0\pi^0$ Z distributions agree well, and we place a limit of 0.7×10^{-4} for the possible bias from the neutral-mode acceptance.

Other checks on the acceptance include data/MC comparisons of track illuminations at the drift chambers and CsI, photon illumination at the CsI, and minimum photon separation distance at the CsI. These all agree well and indicate no other sources of acceptance misunderstanding.

The final class of systematics includes possible differences in the K_S/K_L flux ratio between the $\pi^+\pi^-$ and $\pi^0\pi^0$ samples. The fact that using $\pi^+\pi^-$ and $\pi^0\pi^0$ data from different running periods is of little concern because the regenerator and movable absorber were the same for both periods; however, we still assign a small uncertainty due to a possible temperature difference which might change their densities and thus the regenerator-beam attenuation. In addition,

Table 1
Systematic uncertainties on $\mathrm{Re}(\epsilon'/\epsilon)$.

	Uncertainty ($\times 10^{-4}$)		
Source of Uncertainty	$\pi^+\pi^-$		$\pi^0\pi^0$
1. Data Collection			
Trigger and Level 3 filter	0.5		0.3
2. Reconstruction, Selection, Backgrounds			
Energy scale	0.1		0.7
Calorimeter nonlinearity	...		0.6
Detector calibration, alignment	0.3		0.4
Analysis cut variations	0.6		0.8
Background subtraction	0.2		0.8
3. Detector Acceptance			
Limiting apertures	0.3		0.5
Detector resolution	0.4		<0.1
Drift chamber simulation	0.6		...
Z dependence of acceptance	1.6		0.7
Monte Carlo statistics	0.5		0.9
4. Kaon Flux and Physics Parameters			
Regenerator-beam attenuation:			
1996 versus 1997		0.2	
Energy dependence		0.2	
Δm, τ_S, regeneration phase		0.2	
TOTAL		2.8	

a small difference in the energy dependence of the attenuation (measured using $\pi^+\pi^-\pi^0$ and $3\pi^0$ data) leads to a small uncertainty on $\mathrm{Re}(\epsilon'/\epsilon)$.

Finally, we assign uncertainties corresponding to one-sigma variations of Δm and τ_S from the PDG values [10], and from a deviation of the phase of the regeneration amplitude by $\pm 0.5°$ from the value given by analyticity [15]. Adding all contributions in quadrature, the total systematic uncertainty on $\mathrm{Re}(\epsilon'/\epsilon)$ is 2.8×10^{-4}.

We have performed several cross-checks on the $\mathrm{Re}(\epsilon'/\epsilon)$ result. Consistent values are obtained at all kaon energies (see Fig. 5), and there is no significant variation as a function of time or beam intensity. Relaxing the power-law constraint on the regeneration amplitude yields a consistent value with the same precision.

We have also extracted $\mathrm{Re}(\epsilon'/\epsilon)$ using an alternative fitting technique which compares the vacuum- and regenerator-beam Z distributions directly, eliminating the need for a Monte Carlo simulation to determine the acceptance. While statistically less powerful, this technique yields a value of $\mathrm{Re}(\epsilon'/\epsilon)$ which is consistent with the standard analysis based on the uncorrelated parts of the statistical and systematic errors. In the end, using $\pi^+\pi^-$ data from 1996 (collected simultaneously with the $\pi^0\pi^0$ data) instead of from 1997 yields a consistent value of $\mathrm{Re}(\epsilon'/\epsilon)$, 25×10^{-4}, allowing for a larger systematic error of 4×10^{-4} due to the 1996 Level 3 inefficiency.

6. Conclusion for $\mathrm{Re}(\epsilon'/\epsilon)$

We measured $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 3.0\ (stat) \pm 2.8\ (syst)) \times 10^{-4}$; combining errors in quadrature, $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$. This result [12], nearly 7σ above zero, firmly estab-

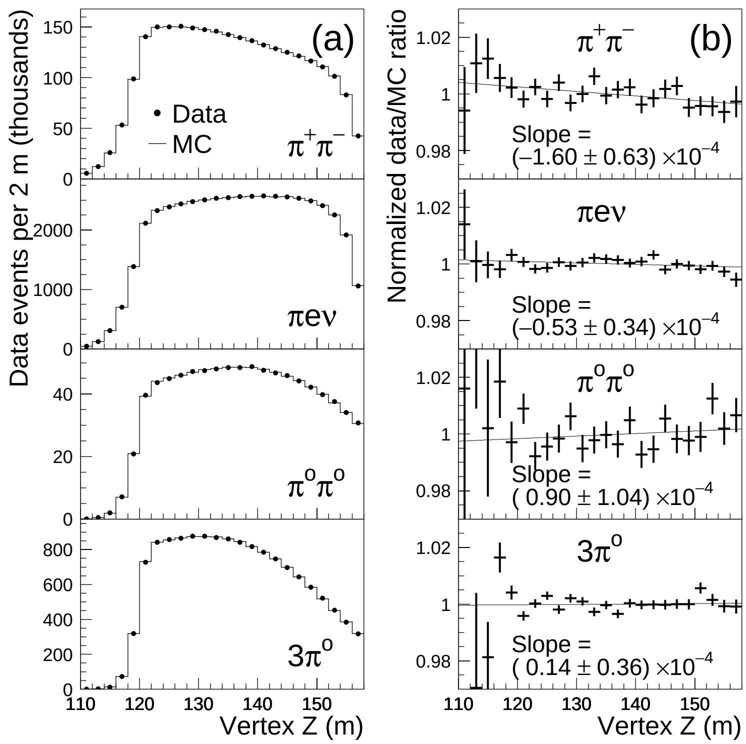

Figure 4. (a) Data versus Monte Carlo comparisons of vacuum-beam decay vertex Z distributions for $\pi^+\pi^-$, $\pi e\nu$, $\pi^0\pi^0$, and $3\pi^0$ decays. (b) Linear fits to the data/MC ratio of Z distributions for each of the four decay modes.

lishes the existence of CP violation in a "decay process", agreeing better with the earlier measurement from NA31 than with E731 [16] (Fig. 6) and shows that a superweak interaction cannot be the sole source of CP violation in the K meson system. The average of the three measurements (KTeV, NA31 and E731), $(21.7 \pm 3.0) \times 10^{-4}$, while at the high end of standard-model predictions, supports the notion of a nonzero phase in the CKM matrix. Further theoretical and experimental advances are needed before one can say whether or not there are other sources of CP violation beyond the standard model.

7. CPT Results on Δm, τ_S, $\Delta\phi$ and ϕ_{+-}

With the $K_S - K_L$ interference downstream of the regenerator beam (see Fig. 7) we have also performed the fits to extract Δm, τ_S, ϕ_{+-} and $\Delta\phi$ as a test of CPT symmetry without assuming CPT invariance. The result for Δm is $\Delta m = (0.5286 \pm 0.0023) \times 10^{-10}\ \hbar\mathrm{s}^{-1}$ and for ϕ_{+-} is

$$\begin{aligned}\phi_{+-} &= (43.66 \pm 0.30)^\circ \\ &+ \quad 0.23^\circ \times \frac{\Delta m - 0.5286}{0.0010} \\ &- \quad 0.26^\circ \times \frac{\tau_s - 0.8967}{0.0010}. \end{aligned} \tag{4}$$

The ϕ_{+-} value is in excellent agreement with $\phi_{SW} = (43.5 \pm 0.08)^\circ$ [10] in the limit of CPT invariance and the Δm is also in good agreement with the fit assuming CPT ($\phi_{+-} = \phi_{SW}$) and the τ_S is $(0.8967 \pm 0.0007) \times 10^{-10}$ s. The fit χ^2 is 234 for 214 degrees of freedom. The Δm result agrees well with all the recent measurements since 1992, but about 2σ lower than earlier measurements. The τ_S result is somewhat higher than PDG average which is affected by the correlation with

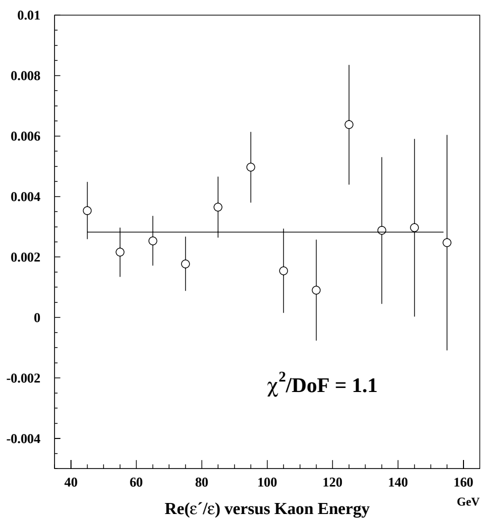

Figure 5. A systematic check of $\mathrm{Re}(\epsilon'/\epsilon)$ vs kaon energy.

Δm.

Another test for CPT is to measure the CPT-violating phase difference $\Delta\phi = \phi_{00} - \phi_{+-}$ and we get

$$\begin{aligned}\Delta\phi &= (0.09 \pm 0.43(\mathrm{stat}) \pm 0.15(\mathrm{syst}))^\circ \\ &= (0.09 \pm 0.46)^\circ, \end{aligned} \tag{5}$$

consistent with zero. The grand average is then $\Delta\phi = (-0.01 \pm 0.40)^\circ$. Assuming $\Gamma_{K^0} = \Gamma_{\overline{K}^0}$, the above results would give the bound for $K^0 - \bar{K^0}$ mass difference,

$$\frac{\Delta m}{m_K} = \frac{m_{K^0} - m_{\overline{K}^0}}{m_K} = (4.5 \pm 3) \times 10^{-19}. \tag{6}$$

Finally, we have also tested the CPT-violating hypothesis that there might be a diurnal variation of ϕ_{+-} with respect to sidereal time suggested by [17]. Figure 8 shows our ϕ_{+-} versus Greewich mean sidereal time and the fit of sine variation gives $(0.34 \pm 0.27)^\circ$ over 24 hours period, consistent with zero. Therefore, the CPT invariance in $K^0 \to \pi\pi$ has been tested very precisely and holds well.

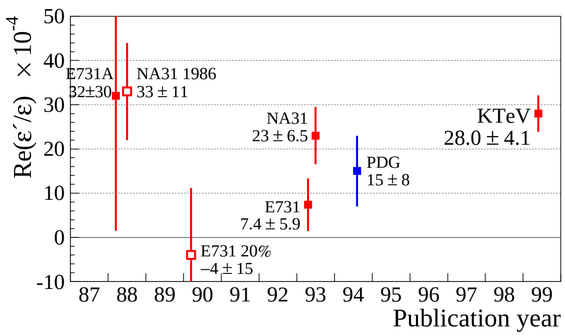

Figure 6. Comparison of the $\mathrm{Re}(\epsilon'/\epsilon)$ measurements since 1986.

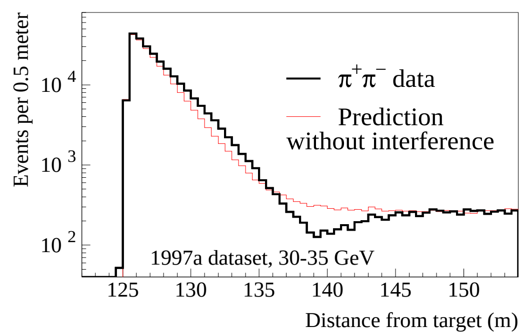

Figure 7. The interference between K_S and K_L behind the regenerator for $\pi^+\pi^-$ mode.

8. Future Prospects

More data from KTeV are currently being processed through calibration and analysis to reduce both statistical and systematic uncertainties. At the same time, we have been taking more data again in 1999 with the aim of doubling the statistics for ϵ'/ϵ with much improved detector performance and additional systematic checks. We expect to reduce the $\mathrm{Re}(\epsilon'/\epsilon)$ statistical uncertainty to $\sim 1 \times 10^{-4}$ and lower the systematics to a similar level.

In a few years we expect $\mathrm{Re}(\epsilon'/\epsilon)$ can be precisely measured by experiments such as KTeV, NA48 and KLOE to 5-10% of itself, which would challenge the theorists to refine their calculations

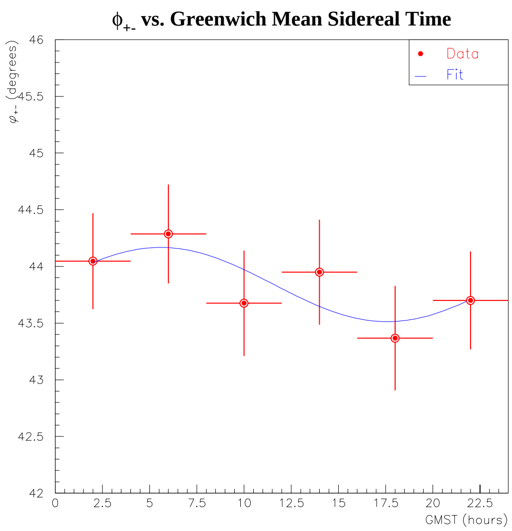

Figure 8. Diurnal fit for the ϕ_{+-} vs Greenwich mean sidereal time.

for the origin of direct-CP violation. This may well be the most precise measurement in search for "direct" CP violation in the next 5 to 10 years before upcoming B-physics experiments and the next generation $K_L \to \pi^0 \nu \bar{\nu}$ experiments, such as KAMI, BNL-926 and KEK-PS-391 [18]. The $K_L \to \pi^0 \nu \bar{\nu}$ decay though very challenging experimentally, is essentially pure direct CP violation and can be calculated theoretically very precisely and cleanly [19]. Its branching ratio depends directly on the CP-violating phase of the Standard CKM Model with little theoretical uncertainty. Therefore, an observation of $K_L \to \pi^0 \nu \bar{\nu}$ signal events in the predicted range would measure directly the magnitude of CP-violating phase in CKM matrix elements. An observation of $K_L \to \pi^0 \nu \bar{\nu}$ outside the range predicted by standard model would indicate new physics [20].

The rest data taking of KTeV in 1999 will be devoted to rare decay search program in neutral kaon and neutral hyperons, as well as continuing the study of $K_L \to \pi^0 \nu \bar{\nu}$ in preparation for the future KAMI experiment.

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