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OBSERVATION OF DIRECT-CP VIOLATION - ϵ'/ϵ FROM KTeV

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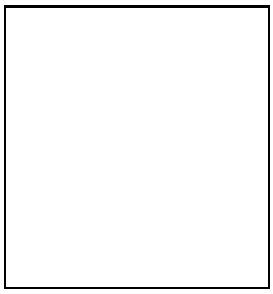

We report the first KTeV measurement for the search of direct-CP violation by using 23% of the data sample collected in the 1996-97 fixed target run at Fermilab, . The result is, $\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$, nearly 7σ above zero obtained by a blind analysis. This 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.

1 Introduction

Thirty-five years after the first unexpected discovery of CP-violation in $K_L \to \pi\pi$ decays in 1964,[1] 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?" 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 accomodates CP violation with a complex phase in the quark mixing matrix,[3] 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] had given non-zero values slightly below 10^{-3}; however, another group gave a somewhat larger estimates.[5] Alternatively, a "superweak" interaction [6] 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 and CERN-NA31 were $(7.4 \pm 5.9) \times 10^{-4}$ (E731),[7] $(23.0 \pm 6.5) \times 10^{-4}$ (NA31),[8] and the PDG average [9] was $(15 \pm 8) \times 10^{-4}$ which gave inconclusive interpretations between standard model or superweak CP violation. New experiments have been constructed at Fermilab(KTeV), CERN(NA48),[10] and Frascati(KLOE) to measure $\mathrm{Re}(\epsilon'/\epsilon)$ with a precision of $\sim 1 \times 10^{-4}$ for the search of "direct-CP" violation effect and determining its magnitude.

We report here a new measurement of $\mathrm{Re}(\epsilon'/\epsilon)$ from 23% of the data sample collected by the KTeV experiment (in E832 run) during 1996-97 fixed target run at Fermilab. This result has recently been published [11] after the first preliminary announcement in February 24, 1999.

2 KTeV Experiment 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 [12] is the same as in E731 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 1.7 m scintillators and is fully active to reduce the scattered background to the coherently regenerated K_S.

The KTeV detector has been shown in elsewhere.[11] 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 as a function of Z, the decay distance from the target. Therefore, the most crucial requirement of measuring $\mathrm{Re}(\epsilon'/\epsilon)$ with this technique is a precise understanding of the Z-dependence of the detector acceptance.

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 (L3) 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 have led to a larger systematic error.

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

Source of Uncertainty	Uncertainty ($\times 10^{-4}$) $\pi^+\pi^-$	$\pi^0\pi^0$
1. Data Collection		
Trigger and L3 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	

The L3 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 in 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. Detailed analysis cuts and selections, background subtractions and estimates of $\pi^+\pi^-$ and $\pi^0\pi^0$ candidates are described elsewhere.[11] The final samples consist of events with $110 < Z < 158\ m$ and $40 < E_K < 160\ GeV$. 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. Backgrounds are small and can be simulated well with small uncertainties.

$\mathrm{Re}(\epsilon'/\epsilon)$ 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.[9] 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.[12] [14] The kaon energy distribution are also allowed to float for $\pi^+\pi^-$ and $\pi^0\pi^0$ modes in each energy bin. 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 $\chi^2/d.o.f = 30/21$.

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 our publication.[11]

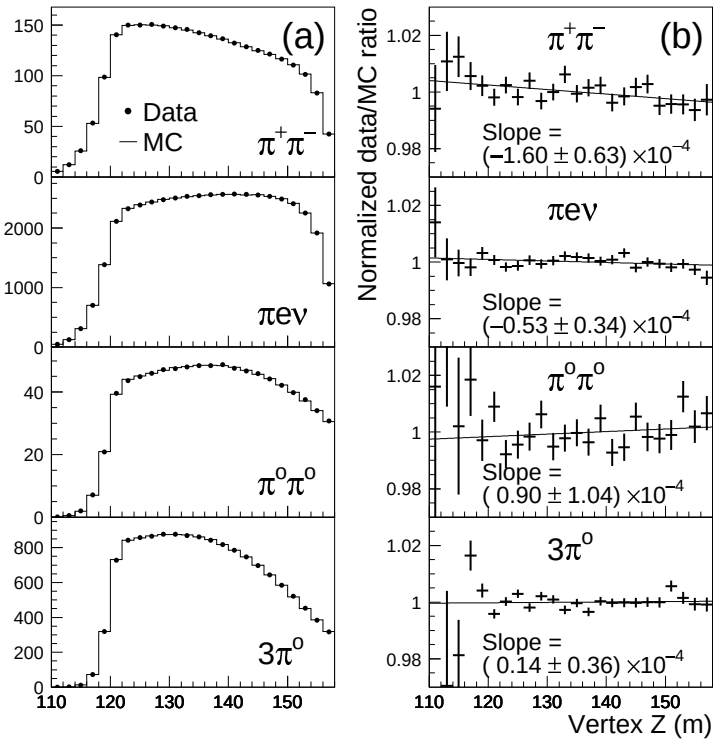

Figure 1: (a) Data versus Monte Carlo comparisons of vacuum-beam decay vertex Z distributions for $\pi^+\pi^-$, $\pi e\nu$, $\pi^0\pi^0$, and $3\pi^0$ decays. (b) Linear fits to the data/MC ratio of Z distributions for each of the four decay modes.

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 1 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 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. 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. 1 (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.

We have performed many cross-checks on the $\mathrm{Re}(\epsilon'/\epsilon)$ result. Consistent values are obtained at all kaon energies, 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) 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 L3 inefficiency.

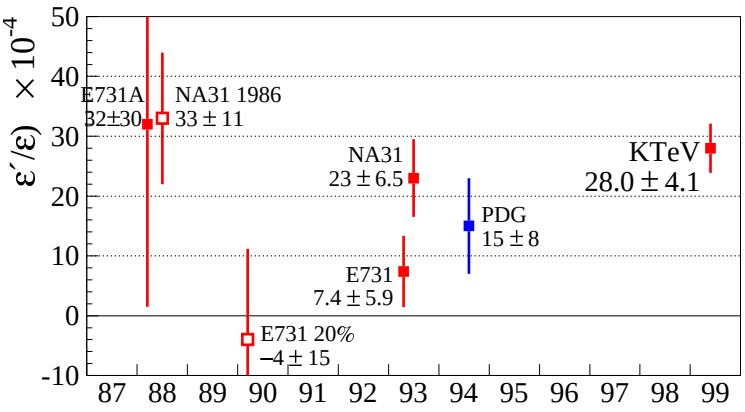

Figure 2: Comparison of the Re(ϵ'/ϵ) measurements since 1986.

4 Conclusion for Re(ϵ'/ϵ)

We measured Re(ϵ'/ϵ) = $(28.0 \pm 3.0\ (stat) \pm 2.8\ (syst)) \times 10^{-4}$; combining errors in quadrature, Re(ϵ'/ϵ) = $(28.0 \pm 4.1) \times 10^{-4}$. This result,[11] nearly 7σ above zero, firmly establishes the existence of CP-violation in a "decay process", agreeing better with the earlier measurement from NA31 than with E731,[15] as shown in Fig. 2. This result 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.[16] The recent preliminary NA48 measurement [10] gives Re(ϵ'/ϵ) = $(18.5 \pm 7.3) \times 10^{-4}$, in excellent agreement with the above average value.

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