Measurement of direct CP violation in K meson decays at KTeV

A. Glazov[a]

[a]University of Chicago, 5640 South Elis Ave, Chicago Il, 60637, USA

The first measurement of direct CP violation parameter $Re(\epsilon'/\epsilon)$ from the KTeV experiment at Fermilab is presented in this paper. Using a subset of data collected in 1996 and in 1997 we find that $Re(\epsilon'/\epsilon) = [28.0 \pm 3.0(stat) \pm 2.8(syst)] \times 10^{-4}$ [1].

1. INTRODUCTION

The neutral K meson system provides an extremely precise natural laboratory to study various small effects which have fundamental importance for physics. This is due to mixing of two strangeness states ($K^0, \overline{K}^0$) to produce the observable long- and short-lived K mesons (K_S, K_L) with tiny mass splitting. One of the most striking discoveries was observation of decays $K_L \to \pi\pi$ in 1994 [2] revealing the CP symmetry violation.

The gross features of this effect is an asymmetry in the $K^0 - \overline{K}^0$ mixing, parameterized by ϵ and called *indirect* CP violation. The other possibility, CP violation in decay process itself, parameterized by ϵ' and called *direct* CP violation has been of the great interest. If present, it would contribute differently to the decay rate into different two π final states. Thus, it can be measures as

$$Re(\epsilon'/\epsilon) = \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}\right]. \tag{1}$$

The Standard Model describes CP violation in a natural way with a complex phase in the quark mixing matrix. However, the calculations of $Re(\epsilon'/\epsilon)$ are very involved. At present the low energy part of the problem, the calculation of hadronic matrix elements, introduces the largest uncertainty to the Standard Model prediction. Most of recent estimates give values near or below 10^{-3}, for example, $(4.6\pm3.0)\times10^{-4}$[3] and $(8.5\pm5.9)\times 10^{-4}$[4]. There are also estimates with somewhat larger range of values, $(17^{+14}_{-10}) \times 10^{-4}$[5]. Alternatively, the indirect CP violation can be also described by additional "superweak" interaction. In this case $Re(\epsilon'/\epsilon) = 0$. Therefore, a nonzero value of $Re(\epsilon'/\epsilon)$ rules out the possibility that a superweak interaction is the sole source of CP violation[6].

The two most precise past measurements of $Re(\epsilon'/\epsilon)$ performed at Femilab (E731) and at CERN (NA31) reported $Re(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4}$[7] and $Re(\epsilon'/\epsilon) = (23 \pm 6.5) \times 10^{-4}$[8], respectively. Because of importance to definitively establish direct CP violation new experiments have been undertaken at Fermilab, CERN and Frascati to measure $Re(\epsilon'/\epsilon)$ with precision of about 1×10^{-4}. This paper describes the measurement performed using 23% of the data taken during 1996-1997 run by the KTeV collaboration at Fermilab.

2. THE EXPERIMENT AND DATA ANALYSIS

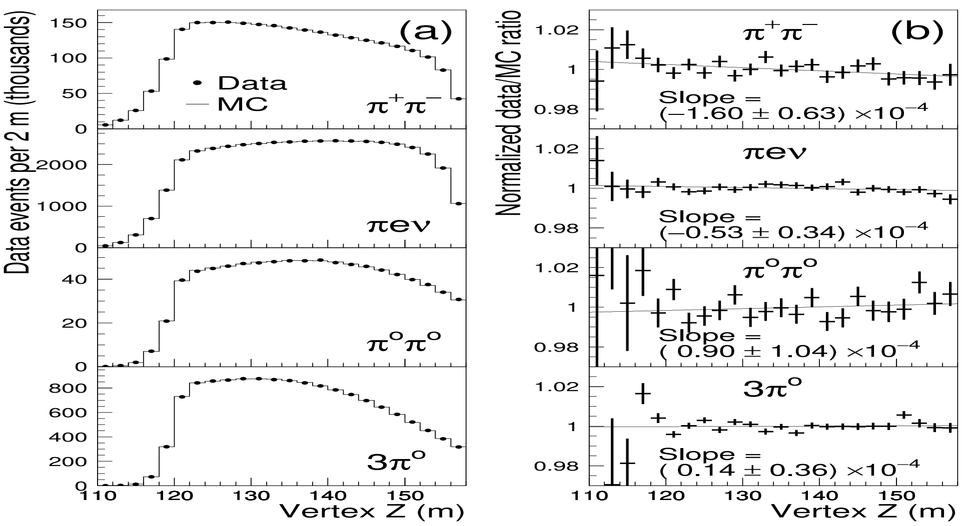

Figure 1. (a) Monte Carlo compared to Data of vacuum beam Z distributions for $\pi^+\pi^-$, $\pi e\nu$, $\pi^0\pi^0$ and $\pi^0\pi^0\pi^0$ decays. (b) Linear fits to ratio of data/MC distributions for these samples.

Descriptions of the KTeV detector can be found elsewhere [9]. The overall detector design is similar to one of E731 [10] but with several improvements of various components. Two parallel K_L beams enter the fiducial decay region 110 meters from the production target. One of the beams passes through scintillator regenerator to produce K_S. We will call this beam as regenerator or K_S beam compared to vacuum or K_L beam. The regenerator position alternates once per minute between the two input beams in order to minimize systematic differences between K_S and K_L events. The regenerator parameters are optimized to increase relative fraction of coherent regeneration compared to inelastic and diffractive processes.

The decay volume is held in vacuum, it extends up to 159 meters from the target. The $\pi^+\pi^-$ decays are measured in drift chamber spectrometer consisting of two stations before and two stations after an analysis magnet with horizontal P_t kick of 0.41 GeV/c. The $\pi^0\pi^0$ decays are detected by a 3100 channel CsI electromagnetic calorimeter located at 186 meters from the target. The decay volume and detector volumes are surrounded by a series of photon vetoes.

The $\pi^+\pi^-$ and $\pi^0\pi^0$ events are selected online using two level hardware trigger and third level software filter farm. In addition high statistics K_L decay modes, $K \to \pi\nu e$, $K \to \pi^0\pi^0\pi^0$ and $K \to \pi^0\pi^+\pi^-$ are collected for detector calibration and study of various systematic effects.

The $\pi^0\pi^0$ samples used for this analysis are from data collected in 1996 while the $\pi^+\pi^-$

samples are from beginning of KTeV data taking in 1997. This is due to 22% filter farm inefficiency in 1996 for $\pi^+\pi^-$ events because of too strict reconstruction criteria for the tracks in the drift chambers. Although this inefficiency is almost identical for both beams it would still lead to a large systematic uncertainty in $Re(\epsilon'/\epsilon)$. After the modification of the level 3 software for the 1997 run the event loss was reduced to below 1%. Using $\pi^+\pi^-$ and $\pi^0\pi^0$ data from different periods does not significantly increase systematic uncertainty in $Re(\epsilon'/\epsilon)$ since the two modes are reconstructed in essentially independent detector subsystems, detector inefficiencies and dead time effects cancel in single ratio of K_L to K_S yields for either mode.

As a general rule any bias affecting K_L and K_S beams differently leads to systematic uncertainty in $Re(\epsilon'/\epsilon)$. The essence of KTeV detector design is to minimize detection differences for K_S and K_L events. But some of them are fundamentally irreducible, the most important one being the difference in the life time. For KTeV energies the mean decay length of K_S is on the level of few meters compared to few kilometers for K_L. This leads to very different distributions of the decay position along the beam (Z-coordinate). Clearly, understanding of detector acceptance in Z is of a crucial importance for $Re(\epsilon'/\epsilon)$ measurement. We use Monte Carlo simulation to determine it.

Figure 1 shows the comparison of vacuum beam Z distributions for both signal and calibration decay modes. One can see that the overall agreement for all modes is very good. This is especially true in case of $\pi^0\pi^0$ and $\pi^0\pi^0\pi^0$ events, where the ratios of data to Monte Carlo Z distributions show no slope within statistical error. On the other hand, there is about 2.5σ slope in case of $\pi^+\pi^-$ events. Since the mean Z positions for K_L and K_S decays differ by about 6 m, this slope corresponds to 1.6×10^{-4} uncertainty in $Re(\epsilon'/\epsilon)$ – the largest source systematic error in this analysis.

Another example of intrinsic difference between vacuum and regenerator beam is background due to incoherent scattering off regenerator. The inelastic scatters are detected by photo-multiplier tubes attached to the regenerator and largely suppressed even at the trigger level. The diffractive scattering can be tagged for $\pi^+\pi^-$ events measuring transverse momentum with respect to direction of the K meson beam. The level of remaining background for $\pi^+\pi^-$ mode is below 0.1%, it has negligible contribution to the systematic uncertainty.

The background level is much larger for $\pi^0\pi^0$ samples since the directions of the decay products are not reconstructed. Requirement of the energy centroid to be within the beam region allows to reduce the scattering background to about 1.2% level. Uncertainties in modeling of this background contribution lead to 0.8×10^{-4} error in $Re(\epsilon'/\epsilon)$.

Other sources of systematic uncertainties are discussed in [1]. The total systematic uncertainty in $Re(\epsilon'/\epsilon)$ is calculated as a quadratic sum of all individual sources. It is found to be equal to 2.8×10^{-4} compared to statistical uncertainty of 3.0×10^{-4}. Many sources of systematic uncertainty, including the dominant ones, have essentially statistical nature. They can be reduced using the total event sample collected at KTeV.

3. RESULTS

$Re(\epsilon'/\epsilon)$ and other K meson system parameters are extracted from the background subtracted data using a fitting program which calculates decay vertex distributions, properly treating regeneration and $K_S - K_L$ interference. K_L and K_S mass difference, ΔM; K_S life time, τ_S; decay phase for $\pi^0\pi^0$, ϕ_{00} and for $\pi^+\pi^-$ events, ϕ_{+-} are calculated for both $\pi^+\pi^-$ and $\pi^0\pi^0$ samples. Consistent results are found leading to the following preliminary KTeV result:

$$\begin{aligned} \Delta m &= (0.5200 \pm 0.0013) \times 10^{-10} \hbar s^{-1} \\ \tau_S &= (0.8967 \pm 0.0007) \times 10^{-10} s \\ \Delta\phi &= \phi_{+-} - \phi_{00} = 0.09^o \pm 0.46^o \end{aligned} \tag{2}$$

Fitting of $Re(\epsilon'/\epsilon)$ was done "blind", by hiding the value of $Re(\epsilon'/\epsilon)$ with an unknown offset, until after the systematic error evaluation were finalized. The result is:

$$Re(\epsilon'/\epsilon) = [28.0 \pm 3.0(stat) \pm 2.8(syst)] \times 10^{-4} = (28.0 \pm 4.1) \times 10^{-4} \tag{3}$$

where the final error is obtained by adding the statistical and systematic uncertainty in quadrature.

This result definitively establishes the existence of direct CP violation agreeing better with earlier measurement from NA31 than with E731, and shows that a superweak interaction cannot be the sole source of CP violation in the K meson system. Recently NA48 collaboration at CERN announced a new preliminary result on $Re(\epsilon'/\epsilon) = 18.5 \pm 7.3$ which is consistent with all measurements. The average of all four results, $(21.3 \pm 2.8) \times 10^{-4}$, while at the high end of standard model predictions, supports the notion of a nonzero phase in the CKM matrix.

New results on $Re(\epsilon'/\epsilon)$ from KTeV collaboration are expected soon. They will be based on data sample taken in 1997 and 1999 which is about eight times bigger than reported here allowing to reduce statistical uncertainty in $Re(\epsilon'/\epsilon)$ to 1×10^{-4} level. The final goal of the analysis is to reduce total systematic error below 1×10^{-4} leading to combined uncertainty in $Re(\epsilon'/\epsilon)$ of about 1.5×10^{-4}.

REFERENCES

1. A. Alavi-Harati *et al.* Phys. Rev. Lett. **83**, 22 (1999).
2. J.H Chistenson, J.W. Cronin, V.L. Fitch, and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
3. M. Ciuchini, Nucl. Phys. (Proc. Suppl.) **59**, 149 (1997).
4. A.J. Buras, in *Probing the Standard Model of Particle Interactions*, edited by R. Gupta *et al.* (Elsevier, New York, 1999); hep-ph/9806471.
5. S. Bertolini *et al.*, Nucl. Phys. **B514**, 93 (1998).
6. L. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964); Comments Nucl. Part. Phys. **21**, 275 (1994).
7. L.K. Gibbons *et al.*, Phys. Rev. Lett. **70**, 1203 (1993).
8. G.D. Barr *et al.*, Phys. Lett. B **317**, 233 (1993).
9. R. Kessler, Proc. VII of Heavy Quarck at Fixed Target (HQ96) (ed. L. Kopke, Rhinefels 1996) 321 (1997).
10. L.K. Gibbons *et al.* Phys. Rev. D **55**, 6625 (1997).