Review on $\epsilon'/\epsilon$

Taku Yamanaka
Osaka University, Osaka, Japan

Experiments at CERN and Fermilab have been competing each other to improve the measurement of a CP violation parameter, $Re(\epsilon'/\epsilon)$. Fermilab KTeV-E832 recently announced their final result, $Re(\epsilon'/\epsilon) = [19.2 \pm 2.1] \times 10^{-4}$. The new world average shows the existence of direct CP violation in the decay process itself with 12 standard deviations.

I. INTRODUCTION

Violation of CP conservation was first observed in the $K_L \to \pi^+\pi^-$ decay [1], in which CP “odd” $K_L$ was decaying into CP even $\pi^+\pi^-$ state. This phenomena is referred to as indirect CP violation, because it is caused by an imaginary phase in the $K^0 - \bar{K}^0$ ($\Delta S = \pm 2$) transition amplitude. This phase adds small amount of CP even final state. This is called $CP$ even in the ratio of partial decay widths, $\text{Re}(\epsilon'/\epsilon)$

Since the required accuracy on $\epsilon'$ is $10^{-4}$, systematic errors had to be controlled to a smaller level, which was challenging experimentally.

II. PAST RESULTS

There have been two major efforts in the world; one at CERN and one at Fermilab, competing each other to make precise and accurate measurements.

A. CERN NA31 and NA48 Experiments

The original experiment at CERN, NA31 [2], had one kaon beam, and had $K_L$ runs with a target far upstream, and separate $K_S$ runs with a production target moving in the decay region. In this scheme, the detector rates were not exactly the same between $K_L$ and $K_S$ runs.

The improved experiment at CERN, NA48, used two production targets to make $K_L$ and $K_S$ beams simultaneously, as shown in Fig. 1. The two beams merged at the detector region, and $K_S$ decays were identified by protons passing through a set of tagging counters just before hitting the $K_S$ production target. For $\pi^+\pi^-$ decays, the decay vertex and the momenta of the pions were measured for each set of drift chambers and a spectrometer magnet. For $K_L \to K^0\pi^0$ decays, the energies and hit positions of photons were measured by a liquid krypton calorimeter. The decay vertex position was reconstructed by assuming the kaon mass for the four photon invariant mass. The reconstructed decay vertex position distribution for $K_L$ decays was weighted to have the same distribution as $K_S$ decays, to reduce systematic errors. Their final result [3] is $Re(\epsilon'/\epsilon) = [14.7 \pm 2.2] \times 10^{-4}$, showing a clear deviation from zero.

B. Fermilab E731 and KTeV-E832 Experiments

The E731 experiment [4] at Fermilab used a $K_L$ beam and a regenerated $K_S$ beam, and observed the four modes simultaneously. Its sensitivity was limited by the beam intensity and performance of the lead glass electromagnetic calorimeter.

To run at higher beam intensity and to improve systematic errors, the KTeV-E832 experiment was built with a completely new beam line and detector. The collaboration had two runs, and their result [5] from the first run in 1997, $Re(\epsilon'/\epsilon) = [20.7 \pm 1.48(\text{stat.}) \pm 2.39(\text{syst.})] \times 10^{-4}$, showed a $7\sigma$ deviation from zero. Since then, they have improved their simulation and analysis, and have recently announced their new and final result based on the full data set.
There were many improvements on the Monte Carlo simulation and data analysis. For example, for $\pi^+\pi^-$ decay mode, the chamber resolution was measured as a function of the position within the drift cell and this measurement was used in Monte Carlo simulation and track reconstruction. In addition, the simulation modeled $\delta$-rays crossing multiple cells in the chamber, bremsstrahlung downstream of the magnet, hadronic interactions, and $dE/dx$ in materials ($\sim 4.5\text{MeV}$). As shown in Fig. 3 all these small improvements made the distribution of transverse momentum of the $2\pi$ track system agree better between data and Monte Carlo simulation, reducing the corresponding systematic uncertainty from $0.25 \times 10^{-4}$ in the previous result to $0.10 \times 10^{-4}$.

![FIG. 3: The distribution of the square of the transverse momentum of the $\pi^+\pi^-$ system, $P_T^2$, for left:vacuum ($K_L$) and right:regenerator ($K_S$) beams. The dots show data, and the histogram (MC) shows Monte Carlo simulation for signal plus background.](image)

For the $\pi^0\pi^0$ mode, the light uniformity and non-linearity of the CsI were corrected for in each crystal. Electromagnetic showers were simulated with finite incident angles, and $13\mu\text{m}$ thick Aluminized Mylar wrappings and shims between crystals were also added to the simulation. With these improvements, Monte Carlo simulation reproduced the shower shape better, as shown in Fig. 2. The reconstructed kaon mass dependence on the photon incident angle and kaon energy also agree better between data and Monte Carlo simulation. These better agreements reduced the corresponding systematic uncertainty from $1.47 \times 10^{-4}$ to $0.75 \times 10^{-4}$.

In addition to the data from the 1999 run, KTeV-E832 also reanalyzed the data from the 1997 run. The numbers of observed events after event selections were: $25.1 \text{M}$ for $K_L \rightarrow \pi^+\pi^-$, $43.7 \text{M}$ for $K_S \rightarrow \pi^+\pi^-$, $6.0 \text{M}$ for $K_L \rightarrow \pi^0\pi^0$, and $10.2 \text{M}$ for $K_S \rightarrow \pi^0\pi^0$. The numbers of actual decays in 10 GeV/c kaon momentum bins were calculated by correcting for the acceptance. The acceptance was determined by Monte Carlo simulation, and it was checked with high statistics decay

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modes, such as \( K_L \rightarrow \pi^+e^+\nu \) and \( K_L \rightarrow \pi^0\pi^0 \), as shown in Fig. 5.

The major systematic uncertainties are \( 1.07 \times 10^{-4} \) for background estimation in \( \pi^0\pi^0 \) modes, \( 0.75 \times 10^{-4} \) for CsI cluster reconstruction, \( 0.57 \times 10^{-4} \) for \( \pi^+\pi^- \) mode acceptance, \( 0.48 \times 10^{-4} \) for \( \pi^0\pi^0 \) mode acceptance, and \( 0.48 \times 10^{-4} \) for detector apertures in \( \pi^0\pi^0 \) mode, etc. The total systematic error was reduced from \( 2.39 \times 10^{-4} \) to \( 1.78 \times 10^{-4} \).

The final result on the full KTeV data is \( Re(\epsilon'/\epsilon) = [19.2 \pm 1.1(stat.) \pm 1.8(syst.)] \times 10^{-4} = [19.2 \pm 2.1] \times 10^{-4} \).

Using the same data, KTeV-E832 significantly improved other kaon parameter measurements, \( \Delta m = (5265 \pm 10) \times 10^9 \hbar/s \), \( \tau_S = (89.62 \pm 0.06) \times 10^{-12} \), \( \phi_S = \arg(\eta_\pi) = (44.1 \pm 1.0)^\circ \), and \( \Delta \phi = -3Im(\epsilon'/\epsilon) = (0.30 \pm 0.35)^\circ \).

IV. CONCLUSION

Figure 6 summarizes the results of the \( Re(\epsilon'/\epsilon) \) measurements. Combining the new KTeV result with the past results, the new world average on \( Re(\epsilon'/\epsilon) \) is \([16.8 \pm 1.4] \times 10^{-4}\). The CERN and Fermilab experiments have clearly established the existence of direct CP violation and rejected the Superweak model.

![FIG. 5: (a): From top to bottom, the decay vertex distributions for \( K_L \rightarrow \pi^+\pi^- \), \( K_L \rightarrow \pi^0\pi^0 \), as shown in Fig. 5. (b): The data to MC ratios as a function of the decay vertex position for each decay mode.](image)

![FIG. 6: History of \( Re(\epsilon'/\epsilon) \) measurements.](image)

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