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RESULTS ON *CP* VIOLATION FROM KTeV*

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Fermilab KTeV experiments have clearly established a direct CP violation in $K_{\rm L} \to \pi\pi$ decays, observed a kinematical CP violating effect in $K_{\rm L} \to \pi^+\pi^-e^+e^-$, set new upper limits on the branching ratios of CP violating $K_{\rm L} \to \pi^0\ell\bar{\ell}$ decays. It has also measured form factors and branching ratios of rare $K_{\rm L}$ decays.

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1. Introduction

KTeV experiment at Fermilab consists of two experiments, E832 to measure the CP violation parameter, ε'/ε, and E799 to mainly search for CP violating rare decays. The experiment is a collaboration of Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, Sao Paulo, UCLA, UCSD, Virginia and Wisconsin. We had the first run in 1996–1997, and the second run in 1999–2000.

Figure 1 shows a plan view of the KTeV detector. Kaons were produced by an 800 GeV proton beam that struck a 30 cm long BeO target. Two neutral side-by-side beams were defined by collimators downstream of the target. Charged particles in the beam were swept away by magnets placed after the collimators. The particles from kaons decaying in the decay volume, 90 m–158 m from the target, were detected by the detector described below.

The position and momentum of charged particles were measured using a spectrometer consisting of four drift chambers, two upstream and two downstream of a dipole magnet. The magnet had a momentum kick of 400 (205) MeV/c for E832 (E799). Each chamber consisted of two orthogonal views (x and y), and had approximately 100 μm single-hit position resolution per

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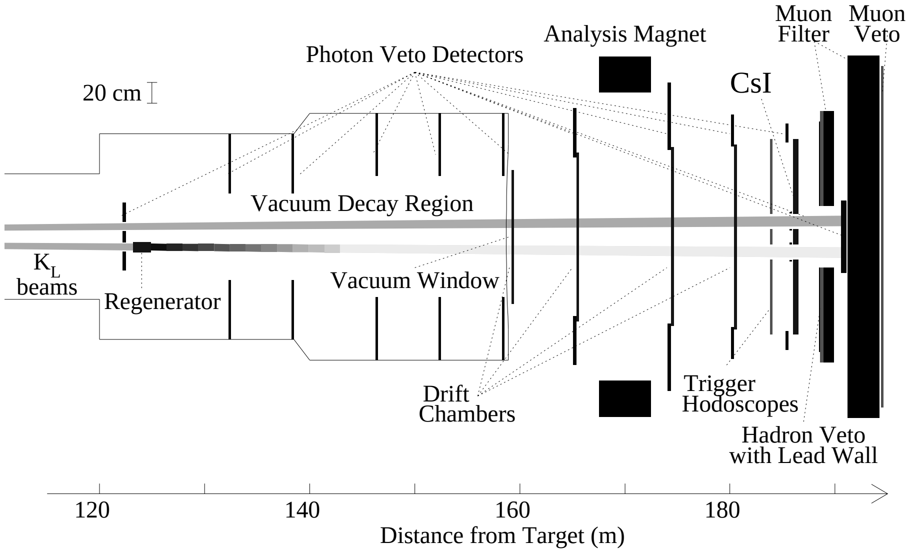

Fig. 1. Plan view of the KTeV experiment.

view. An electromagnetic calorimeter with dimensions of 1.9 m × 1.9 m and 29 X_0 in depth was used for photon detection and electron identification. It was composed of 3100 pure CsI crystals. The energy resolution of the calorimeter was below 1 % averaged over the electron energy range 2 to 60 GeV. Muons were identified or vetoed by scintillator planes located behind a muon filter which was constructed of a 10 cm thick lead wall followed by three steel walls totaling 511 cm thickness. Photons escaping from the decay volume or missing the CsI calorimeter were detected by the ten lead scintillator "photon veto" counters. For E799 rare decay experiment, 8 Transition Radiation Detectors (TRD's) were installed behind the spectrometer for e/π separation.

2. ε'/ε

The CP violation found in 1964 [1] has been explained to be caused by an imaginary phase in K^0–$\overline{K}^0$ mixing. Among many theories, two have survived until recently. One is Superweak model which assumes that there is an interaction which changes the strangeness by 2, and that this new interaction introduces a phase. Another is standard model which brings a phase via quark mixing in a box diagram which changes K^0 to $\overline{K}^0$. One way to distinguish these two theories is to look for CP violation in a decay itself (direct CP violation). For example, Superweak model cannot contribute to the decay $K \to \pi\pi$, since this decay changes the strangeness only by 1. On the other hand, the standard model can introduce a phase in the

$K \to \pi\pi$ decay via gluon or Z penguin diagrams. Therefore, Superweak model predicts that there is no direct CP violation, while the standard model predicts that there is direct CP violation.

The direct CP violation can be searched for by measuring a double ratio,

$$\begin{aligned} R &= \frac{\Gamma(K_{\rm L} \to \pi^+\pi^-)/\Gamma(K_{\rm S} \to \pi^+\pi^-)}{\Gamma(K_{\rm L} \to \pi^0\pi^0)/\Gamma(K_{\rm L} \to \pi^0\pi^0)} \\ &= 1 + 6{\rm Re}\,(\varepsilon'/\varepsilon), \end{aligned} \tag{1}$$

where ε' represents the size of direct CP violation, and ε represents the size of CP violation in the K^0–$\overline{K}^0$ mixing.

KTeV-E832 experiment measured the double ratio by using the two neutral beams. In one of the beams, a regenerator (blocks of scintillators) was placed to produce $K_{\rm S}$, and the other beam was left as a $K_{\rm L}$ beam. The decays from the $K_{\rm S}$ and $K_{\rm L}$ beams were collected simultaneously to cancel various systematic biases. One of the largest systematic errors come from the difference in the decay position distributions between $K_{\rm S}$ and $K_{\rm L}$. If the acceptance was not estimated properly along the decay position, then the number of $K_{\rm S}$ and $K_{\rm L}$ decays will be misestimated. The acceptance was checked by comparing the decay distribution between the data and Monte Carlo simulation for high statistics samples of $K_{\rm L} \to \pi e \nu$ and $K_{\rm L} \to 3\pi^0$ decays.

Based on 23 % of the total data collected in 1996–1997 run, we have published a result [2]: ${\rm Re}\,(\varepsilon'/\varepsilon) = (28.0 \pm 3.0({\rm stat.}) \pm 2.8({\rm syst.})) \times 10^{-4}$ [1]. This result clearly established that the value is not zero, and it was consistent with an earlier result from CERN NA31 [3]: $(23.0 \pm 6.5) \times 10^{-4}$, and CERN NA48 [4]: $(18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$. These results have clearly rejected the Superweak model as a sole source of the CP violation. KTeV is currently analyzing the rest of the data from the 1996–1997 run. We also took a similar amount of data in 1999 with better detector conditions to double the statistics and to have a better understanding of the systematic errors.

3. Searches for *CP* violating rare decays

Another approach to understand the CP violation is to look for rare decays, such as $K_{\rm L} \to \pi^0 e^+ e^-$, $K_{\rm L} \to \pi^0 \mu^+ \mu^-$ and $K_{\rm L} \to \pi^0 \nu \overline{\nu}$. These decays involve penguin diagrams which are also sensitive to the imaginary phase in the CKM matrix.

[1] In June 2001, we have announced a new preliminary result, ${\rm Re}\,(\varepsilon'/\varepsilon) = (20.7 \pm 1.5({\rm stat.}) \pm 2.4({\rm stat.}) 0.5({\rm MC\ stat.})) \times 10^{-4}$ based on the full data sample from 1996 and 1997 run.

3.1. $K_{\rm L} \to \pi^0 e^+ e^-$

KTeV-E799 experiment used two intense $K_{\rm L}$ beams to look for $K_{\rm L} \to \pi^0 e^+ e^-$ decays. After requiring two electrons and two photons consistent with π^0, and applying kinematical cuts to reduce background, we observed 2 events in the signal region where 1.06 ± 0.41 background events were expected. The major background was $K_{\rm L} \to e^+ e^- \gamma\gamma$ decay, which was estimated to be 0.91 ± 0.26 events. Allowing for the background and its uncertainty, we set an upper limit $B(K_{\rm L} \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$ at the 90% C.L. [5], which is one order magnitude better than the previous result.

3.2. $K_{\rm L} \to \pi^0 \mu^+ \mu^-$

Similarly, by requiring two muons and a π^0, we observed two events in the signal region for $K_{\rm L} \to \pi^0 \mu^+ \mu^-$, where 0.87 ± 0.15 events were expected from backgrounds. The major background sources were $K_{\rm L} \to \mu^+ \mu^- \gamma\gamma$ (0.373 ± 0.032 events) and $K_{\rm L} \to \pi^+ \pi^- \pi^0$ with the two pion decays (0.252 ± 0.092 events). We set an upper limit $B(K_{\rm L} \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$ at the 90% C.L. [6].

3.3. Radiative Dalitz background

The fact that we have observed radiative Dalitz decay background events such as $K_{\rm L} \to e^+ e^- \gamma\gamma$ and $K_{\rm L} \to \mu^+ \mu^- \gamma\gamma$ indicates that the sensitivity to the signal events will be statistically limited from now on. Since the decay products of these radiative Dalitz decay modes are exactly the same as the signal decay, and since there are no missing particles, the only handles to reduce the backgrounds are kinematical constraints. In addition, even if we accumulate enough events to separate background events, we still have to untangle contributions from indirect CP violating amplitudes and CP conserving amplitudes. Thus the next main focus on the CP violating rare decays is $K_{\rm L} \to \pi^0 \nu\overline{\nu}$ decay mode.

3.4. $K_{\rm L} \to \pi^0 \nu\overline{\nu}$

The $K_{\rm L} \to \pi^0 \nu\overline{\nu}$ decay is caused by a Z penguin diagram with an intermediate top quark. In a simple picture, $K_{\rm L}$ amplitude is mostly $(K^0 - \overline{K}^0)/\sqrt{2}$, and thus the decay amplitude of $K_{\rm L} \to \pi^0 \nu\overline{\nu}$ is :

$$\begin{aligned} A(K_{\rm L} \to \pi^0 \nu\overline{\nu}) &\propto A(K^0 \to \pi^0 \nu\overline{\nu}) - A(\overline{K}^0 \to \pi^0 \nu\overline{\nu}) \\ &\propto V_{td}^* - V_{td} \\ &\propto {\rm Im}\,(V_{td}) \\ &\propto \eta\,, \end{aligned} \tag{2}$$

where η is the imaginary part of the CKM matrix in the Wolfenstein's parameterization [7]. The branching ratio of $K_{\mathrm{L}} \to \pi^0 \nu\overline{\nu}$ is proportional to the square of the amplitude, so thus to the η^2. The theoretical uncertainty between η and the branching ratio is about 1–2 %. Using the currently known standard model parameters, the branching ratio is estimated to be $(2.8 \pm 1.7) \times 10^{-11}$ [8].

We have searched for the decay using the π^0 Dalitz decay. Although this method loses the sensitivity by more than two orders of magnitude due to its small branching ratio, it allowed us to determine the decay vertex and to measure the mass and the transverse momentum of the π^0. We observed no events in the signal region, and set an upper limit $B(K_{\mathrm{L}} \to \pi^0 \nu\overline{\nu}) < 5.9 \times 10^{-7}$ with the 90 % C.L. [9]. We plan to collect 100 events in the new experiment called KAMI, as described in my another talk.

4. *CP* violation in $K_{\mathrm{L}} \to \pi^+\pi^- e^+e^-$ decays

The $K_{\mathrm{L}} \to \pi^+\pi^- e^+e^-$ decay proceeds through $K_{\mathrm{L}} \to \pi^+\pi^-\gamma^*$ with an internal conversion of γ^* to e^+e^- pair. There are mainly two mechanisms for the $K_{\mathrm{L}} \to \pi\pi\gamma^*$. One is a Direct Emission (DE), where the γ^* is emitted from the $K\pi\pi$ vertex. The other is an Inner Brem (IB), where the γ^* is emitted from an electron line. The CP state is odd for DE and even for IB. The interference between these two generates a CP-violating asymmetry in the CP-odd and T-odd product: $(\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi}) = \sin\phi\cos\phi$, where $\hat{n}_{ee}$ ($\hat{n}_{\pi\pi}$) is the normal vector of ee ($\pi\pi$) plane, $\hat{z}$ is the unit vector in the direction of the $\pi\pi$ in the K_{L} cms, and ϕ is the angle between the ee and $\pi\pi$ planes.

Based on (1811 ± 43) signal events, we observed a raw asymmetry,

$$A = \frac{N^+ - N^-}{N^+ + N^-} = (23.3 \pm 2.3)\,\%\,, \tag{3}$$

where N^+ is the number of events with $\sin\phi\cos\phi > 0$ and *vice versa*. After correcting for the acceptance, the asymmetry was $[13.6 \pm 2.5(\mathrm{stat.}) \pm 1.2(\mathrm{syst.})]\,\%$ [10], which is consistent with a theoretical prediction of $14.3 \pm 1.3\,\%$ using the ε and assuming CPT [11]. This is the first observation of CP violation in a kinematical distribution.

In addition, we found that a form factor was required in the M1 virtual photon emission amplitude to match the observed $E^*_\gamma = E_{e^+} + E_{e^-}$ distribution. By including a form factor,

$$F = \tilde{g}_{M1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E^*_\gamma}\right], \tag{4}$$

we measured

$$\frac{a_1}{a_2} = -0.720 \pm 0.028 \pm 0.009\,\mathrm{GeV}^2/c^2\,,$$

and

$$|\tilde{g}_{\mathrm{M1}}| = 1.35^{+0.20}_{-0.17}(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})\,.$$

We have published [12] the branching ratio $B(K_{\mathrm{L}} \to \pi^+\pi^-e^+e^-) = (3.2 \pm 0.6 \pm 0.4) \times 10^{-7}$ based on one day worth of data. We recently analyzed the full data sample from the 1996–1997 run using optimized cuts and measured $B(K_{\mathrm{L}} \to \pi^+\pi^-e^+e^-) = (3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$ (preliminary), based on 1507.8 events.

5. $K_{\mathrm{L}} \to \pi^+\pi^-\gamma$

The M1 form factor was also measured by using the decay $K_{\mathrm{L}} \to \pi^+\pi^-\gamma$, where a real photon is emitted. Based on 8669 events observed during a fraction of the KTeV-E832 run, we made the first direct measurement [13] of the $K_{\mathrm{L}} \to \pi^+\pi^-\gamma$ direct emission form factor, including $a_1/a_2 = -0.737 \pm 0.034\,\mathrm{GeV}^2$. This result is consistent with the result from the $K_{\mathrm{L}} \to \pi^+\pi^-e^+e^-$ decay described above. In addition, we have improved the normalized branching ratio,

$$\frac{B(K_{\mathrm{L}} \to \pi^+\pi^-\gamma; E^*_\gamma > 20\,\mathrm{MeV})}{B(K_{\mathrm{L}} \to \pi\pi)} = (20.8 \pm 0.3) \times 10^{-3}\,,$$

and

$$K_{\mathrm{L}} \to \pi^+\pi^-\gamma\ \frac{\mathrm{DE}}{\mathrm{DE}+\mathrm{IB}}$$

branching ratio of 0.683 ± 0.011.

6. $K_{\mathrm{L}} \to \gamma^*\gamma^{(*)}$ physics

The decays, $K_{\mathrm{L}} \to e^+e^-\gamma$, $K_{\mathrm{L}} \to \mu^+\mu^-\gamma$, $K_{\mathrm{L}} \to e^+e^-e^+e^-$ and $K_{\mathrm{L}} \to e^+e^-\mu^+\mu^-$ are all related, since they go through $K_{\mathrm{L}} \to \gamma^*\gamma$ or $K_{\mathrm{L}} \to \gamma^*\gamma^*$ with $\gamma^* \to \ell^+\ell^-$. These decays offer information about the form factors, and other interesting physics.

6.1. $K_{\mathrm{L}} \to \mu^+\mu^-\gamma$

Based on 9105 signal events, we measured $B(K_{\mathrm{L}} \to \mu^+\mu^-\gamma) = (3.70 \pm 0.04 \pm 0.07) \times 10^{-7}$ (preliminary) based on 9105 signal events [14]. In addition, a long-distance form factors according to BMS models [15] was measured to be $\alpha_{K^*} = -0.163^{+0.026}_{-0.027}$ (preliminary) based on its branching ratio and the $M_{\mu\mu}$ shape analysis. BMS predict $|\alpha_{K^*}| = 0.25 \pm 0.05$ and $B(K_{\rm L} \to \mu^+\mu^-\gamma) = (4.11 \pm 0.18) \times 10^{-7}$ which is 2.1σ higher than the measured rate. Also, there is a 3σ difference between the measurements of α_{K^*} between $K_{\rm L} \to \mu^+\mu^-\gamma$ and $K_{\rm L} \to e^+e^-\gamma$ [16].

With the understanding of long-distance physics in $K_{\rm L} \to \mu^+\mu^-\gamma$ we can help to set a limit on the CKM parameter, ρ. The branching ratio of $K_{\rm L} \to \mu^+\mu^-$ decay, $(7.15 \pm 0.16) \times 10^{-9}$, is dominated by a contribution from the decay with two intermediate real photons $(7.00 \pm 0.18) \times 10^{-9}$. The rest comes from a short-distance contribution which involves ρ, and a long-distance contribution with $\gamma^*\gamma^*$. Using the measured form factor and DIP model [17], we obtained $\rho > -0.2$ (90 % C.L., preliminary).

6.2. $K_{\rm L} \to e^+e^-e^+e^-$

We observed 441 $K_{\rm L} \to e^+e^-e^+e^-$ candidate events with an estimated background of 4.2 events [18]. We measured $B(K_{\rm L} \to e^+e^-e^+e^-) = (3.72 \pm 0.18(\text{stat.}) \pm 0.23(\text{syst.})) \times 10^{-8}$. We also measured an effective parameter, $\alpha_{K^*}^{\rm eff} = -0.14 \pm 0.16(\text{stat.}) \pm 0.15(\text{syst.})$ which is the form factor by BMS [15] with radiative corrections. We fitted the distribution of angle ϕ between the two e^+e^- planes to

$$\frac{d\Gamma(K_{\rm L} \to e^+e^-e^+e^-)}{d\phi} \propto 1 + \beta_{CP}\cos(2\phi) + \gamma_{CP}\sin(2\phi)\,.$$

Ignoring CP violation, $\beta_{CP} = -0.20$ and $\gamma_{CP} = 0$ for an odd CP eigenstate. We measured $\beta_{CP} = -0.23 \pm 0.09(\text{stat.}) \pm 0.02(\text{syst.})$, and $\gamma_{CP} = -0.09 \pm 0.09(\text{stat.}) \pm 0.02(\text{syst.})$. These results show that the decay predominantly proceeds through CP odd K_2 state.

6.3. $K_{\rm L} \to e^+e^-\mu^+\mu^-$

We observed 38 $K_{\rm L} \to e^+e^-\mu^+\mu^-$ candidate events including 0.18 estimated background events. The branching ratio was measured to be $B(K_{\rm L} \to e^+e^-\mu^+\mu^-) = (2.50 \pm 0.41 \pm 0.15) \times 10^{-9}$ (preliminary) [14]. This confirmed our first observation based on one event, and the measurement [19] $B(K_{\rm L} \to e^+e^-\mu^+\mu^-) = (2.9^{+6.7}_{-2.4}) \times 10^{-9}$. In addition, we set an upper limit on the lepton number violation, $B(K_{\rm L} \to e^\pm e^\pm \mu^\mp \mu^\mp) < 1.36 \times 10^{-10}$ (90 % C.L., preliminary) based on null events in a signal region.

7. Summary

To summarize, Fermilab KTeV Experiment has clearly established an existence of CP violation in the decay process itself, and rejected Superweak model as sole source of CP violation. We set new limits on the branching ratios of CP violating rare decays, $K_{\rm L} \to \pi^0 e^+e^-$, $K_{\rm L} \to \pi^0\mu^+\mu^-$, and $K_{\rm L} \to \pi^0\nu\overline{\nu}$. We observed a CP violating asymmetry in the distribution of the angle between $\pi\pi$ and ee planes in the decay $K_{\rm L} \to \pi^+\pi^-e^+e^-$. We measured a form factor for M1 emission amplitude in $K_{\rm L} \to \pi^+\pi^-e^+e^-$ and $K_{\rm L} \to \pi^+\pi^-\gamma$ decays and obtained consistent results. We measured the $K_{\rm L}\gamma^*\gamma$ form factor in $K_{\rm L} \to \mu^+\mu^-\gamma$ and found that the result is different from the form factor in $K_{\rm L} \to e^+e^-\gamma$. We improved the branching ratios of various $K_{\rm L} \to \mu^+\mu^-\gamma, K_{\rm L} \to e^+e^-e^+e^-$, and $K_{\rm L} \to e^+e^-\mu^+\mu^-$ decays.

KTeV is analyzing the full data set from the 1996–7 run for ε'/ε. We also ran in 1999–2000 to further increase statistics for both ε'/ε analysis and various rare decays.

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