Fermi National Accelerator Laboratory

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Recent Results on CP-Violation from Fermilab Experiment E-731 *

The E-731 Collaboration

presented by

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

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RECENT RESULTS ON CP-VIOLATION FROM FERMILAB EXPERIMENT E731

E731 Collaboration (*Chicago-Elmhurst-Fermilab-Princeton-Saclay*)
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YEE B. HSIUNG
Fermi National Accelerator Laboratory, P.O.Box 500
Batavia, IL 60510, U.S.A.

ABSTRACT

We report the current status of the analysis for the CP-violation parameters, ε'/ε, from the entire data sample of Fermilab experiment E731. A new measurement of the CP-violation parameter $\eta_{+-\gamma}$ was extracted from the K_L-K_S interference of the $\pi^+\pi^-\gamma$ decay mode downstream of a regenerator. The preliminary result, $|\eta_{+-\gamma}| = 0.0020 \pm 0.0002$(stat) $\pm$ 0.0003(syst), is consistent with $|\eta_{+-}|$ from $\pi^+\pi^-$ decay mode. Some results on the measurements of the branching ratio for $K_L \to \pi^+\pi^-\gamma$ and $K_S \to \pi^+\pi^-\gamma$ are presented here. For the very first time, the quadratic decay parameter of $K_L \to 3\pi^0$ has been measured from the $3\pi^0$ Dalitz plot. Our result, $b = (-0.6 \pm 1.4) \times 10^{-3}$, is consistent with zero, indicating a flat Dalitz distribution. It is inconsistent with the fitted result, $b = (-8.3 \pm 2.4) \times 10^{-3}$, from Devlin and Dickey's review.

STATUS OF ε'/ε

Fermilab experiment E731 was designed to measure the "direct" CP violation parameters ε'/ε, which can be expressed as a double ratio of four decay modes of the $K_{L,S} \to \pi^+\pi^-(\pi^0\pi^0)$, *i.e.*

$$R \equiv \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}$$

$$\cong 1 + 6\,Re(\varepsilon'/\varepsilon),$$

where ε describes the K^0-$\bar{K}^0$ mixing and ε' describes the "direct" CP-violation from the decay amplitude. The E731 apparatus has been shown elsewhere [1]. Basically, two nearly identical *side-by-side* K_L beams were brought into the decay region, where a regenerator was placed alternately in one of the K_L beams to produce "K_S". Therefore *simultaneous detection* of both K_L and K_S decays in the same decay region with the same detector became possible. The experiment was designed to minimize systematic uncertainty and in particular to be immune to changes in accelerator cycles and other parameters over which the experimenter has little control, such as *beam intensity and asymmetry, electronic drifts, phototube gain shifts as well as inefficiencies, etc.*

To get the double ratio R, *both* $2\pi^0$ and $\pi^+\pi^-$ decays need to be recorded for *both* K_L and K_S modes. The experiment had its major run in 1987/88. For the majority of the running, either both *charged* ($\pi^+\pi^-$) modes or both *neutral* ($2\pi^0$) modes were recorded simultaneously and this greatly reduced a variety of systematics. For the last 20% of the data, *all four modes* were taken at the same time, providing a best check on the systematics. It is on this data set that we have done the full analysis and recently published a result [2]. We found $\varepsilon'/\varepsilon = -0.0004 \pm 0.0014$ (stat.) $\pm$ 0.0006 (syst.), which is consistent with zero and is two standard deviations below the earlier result from CERN NA31 [3]. From the same data, we also determined the CPT violating phase difference between η_{+-} and η_{00}: $\Delta\phi = -0.3° \pm 2.4°$(stat.) $\pm$ 1.2°(syst.) [4]. This together with a result of similar precision from NA31 [5] in a dedicated experiment resolved a long-standing earlier discrepancy [6] on $\Delta\phi$ which was $12° \pm 6°$.

In the Standard Model, the value of ε'/ε is expected to be non-zero but its precise magnitude depends on, among other parameters, the value of the top quark mass: the higher the mass of the top, the smaller is ε'/ε [7]. Our result clearly favors higher values of m_t in ref. 7 as indicated by the top quark search ($m_t >$ 89 GeV) from the collider experiment [8].

We have made substantial progress in the analysis of the entire data. A result is expected soon in 1991. All of the remaining data has been reduced and the work at present is in the rather delicate calibration of the leadglass detector as well as in the understanding of the acceptance of the apparatus. In Fig. 1 we show the reconstructed $K_{L,S} \to \pi^0\pi^0$ invariant mass distribution for the entire data set, without the final calibration constants. The K_L signal has about 290k events in it (480 to 520 MeV/c^2) while the $3\pi^0$ background is less than 0.5% and is smooth and well understood. The K_S signal has about 970k events in it with a very small background. Since these events were taken simultaneously with the same leadglass detector, the line-shape of the mass peak is virtually identical between K_L and K_S. The incoherent K_S background in the K_L beam (the "crossover" K_S) was quite similar to the one in 20% of the data [2]. The exact amount of the background in the ***neutral*** mode will be determined once we have final leadglass calibration constants.

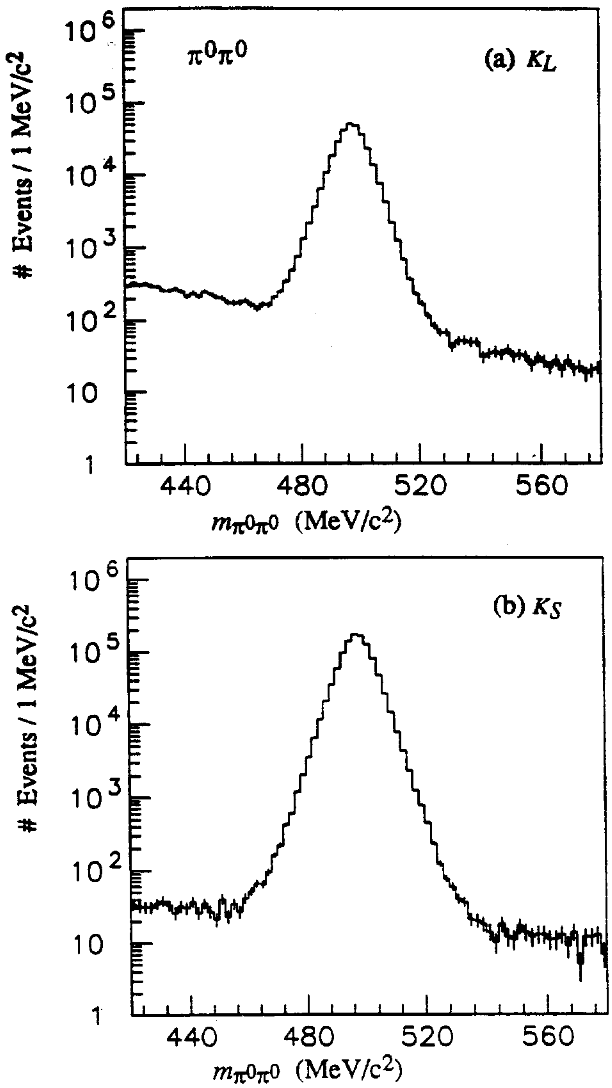

Fig. 1 $\pi^0\pi^0$ mass distribution (a) for K_L and (b) for K_S.

In Fig. 2 we show the reconstructed $K_{L,S} \rightarrow \pi^+\pi^-$ invariant mass distribution of all the data, in which there are 370k K_L and 1.2M K_S in between 484 to 512 MeV/c^2. Comparing this with the 20% of the data, the background level and the line-shape of coherent kaons in the *charged* mode are nearly identical to each other. The background in K_L, can be determined from p_t^2 distribution, is about 0.33% (mainly from the remaining K_{e3}) and in K_S is about 0.14% (from incoherently scattered K_S). With the above statistics, the final statistical error on ε'/ε will be about 0.0005. With better understanding of the detector acceptances, resolutions and energy scales from the current analysis by using the high statistics modes (80M K_{e3}, 10M $3\pi^0$ and 10M $\pi^+\pi^-\pi^0$), we would hope to achieve much smaller systematic uncertainty than that of the 20% data.

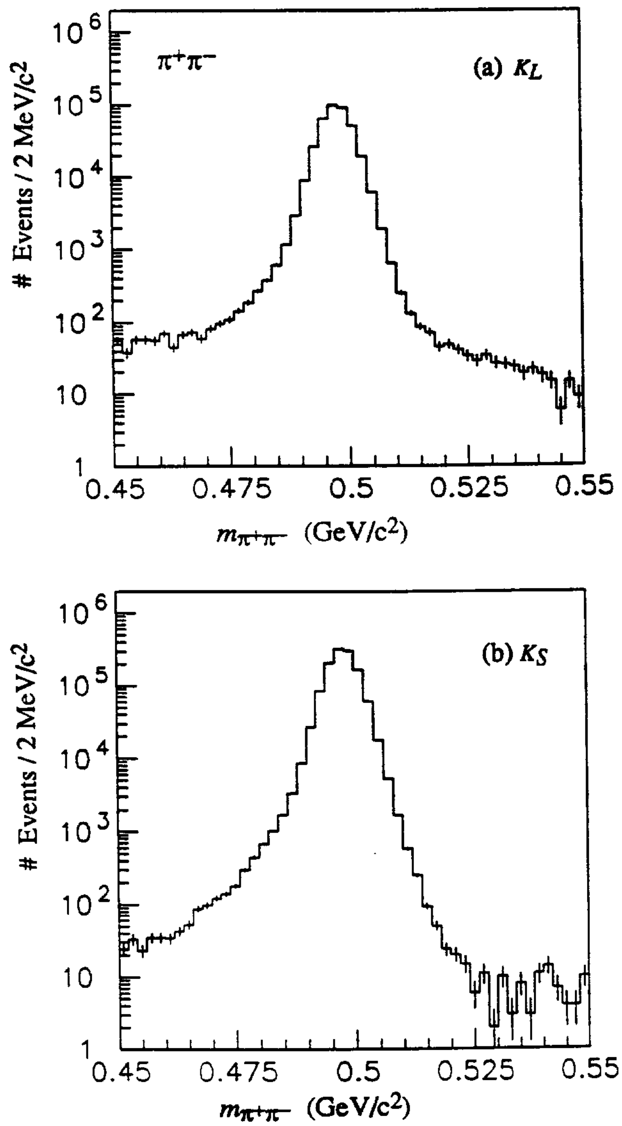

Fig. 2 $\pi^+\pi^-$ mass distribution (a) for K_L and (b) for K_S.

$K_{L,S} \rightarrow \pi^+\pi^-\gamma$

There are two processes by which the neutral kaons decay into $\pi^+\pi^-\gamma$: inner bremstrahlung (IB), where a decay occurs into two charged pions followed by the emission of a photon from one of the pion; and direct emission (DE) decay, where a photon emits from the $\pi\pi$ decay vertex (or one of the quark lines) [9]. Since it is essentially a two-pion decay, the IB process is CP-violating for K_L decays and CP-conserving for K_S, while in the DE process the opposite is true. In Fig. 2(b), the low side non-Gaussian tail of the $\pi^+\pi^-$

mass peak in K_S mainly comes from the radiative IB emission. Since the direct emission is CP-conserving in K_L decay, it is a possible background to ε'/ε. This lead us to measure it's branching ratio and study its contribution to ε'/ε [10].

Event reconstruction requires two opposite-sign charged tracks in the 4 sets of drift chambers and hodoscopes, as well as a separate photon cluster ($E_\gamma >$ 1.5 GeV) in the leadglass calorimeter. Pion selection was done by requiring that each track has $E/p < 0.80$ in the leadglass to reject event containing electrons. Each event was then required to pass fiducial and quality cuts as well as the following kinematic cuts:

(1) track momentum $p > 7$ GeV,
(2) kaon mass cut: $484 < m_{\pi\pi\gamma} < 512$ MeV/c^2,
(3) transverse momentum cut: $p_t^2 < 250$ (MeV/c)^2,
(4) kaon energy cut: $30 < E_K < 160$ GeV,
(5) decay z vertex within 27 m decay region,
(6) a kinematic variable cut: $P_0^2 < -0.025$ [11] to reject $\pi^+\pi^-\pi^0$ decays with one photon escaping the detection.

There were virtually no background events remaining after these selections.

Fig. 3 shows the center of mass photon energy ($E_\gamma{}^*$) spectrum overlayed for the K_L and K_S events, where the K_S spectrum has the inner bremstrahlung $1/k$ distribution and the K_L spectrum has the superposition of IB and DE ($\propto k^3$) distributions. The K_S spectrum has been properly normalized for the subtraction of IB in the K_L spectrum to extract the DE component. With $E_\gamma{}^* > 20$ MeV, we have 4620 K_S decays and 1552 IB and 2607 DE events in the K_L decays. The acceptance for K_S decay is 0.272 and for K_L decay

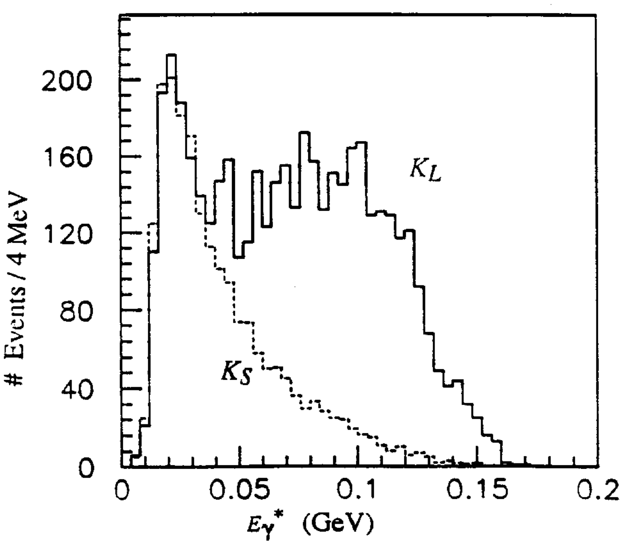

Fig. 3 $E_\gamma{}^*$ distribution of $\pi^+\pi^-\gamma$ for K_L decay (solid line) and K_S decay (dotted line).

is 0.130. The number of kaon decays into $\pi^+\pi^-$ was used to normalize the yield. The branching ratios of neutral kaon decay into $\pi^+\pi^-\gamma$ are $(4.35\pm.08) \times 10^{-5}$ for K_L and $(4.39\pm.07) \times 10^{-3}$ for K_S. The K_L decay has a branching ratio of $(2.98\pm.08) \times 10^{-5}$ into the DE mode and $(1.43\pm.08) \times 10^{-5}$ into the IB mode. This result is consistent with the previous measurement [11] and the theoretical predictions [9].

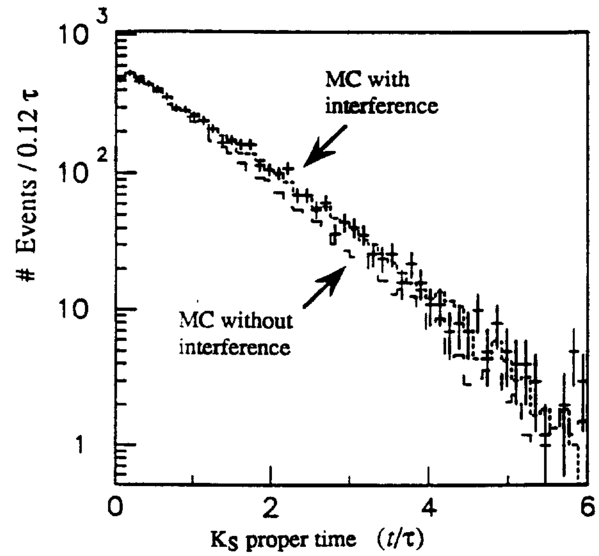

Fig. 4 Proper time distribution for $K_S \to \pi^+\pi^-\gamma$. Data with error bar were superimposed by a monte carlo with (dotted line) and without (broken line) interference term.

Since the coherent kaon beam behind the regenerator is the superposition of $K_L+\rho K_S$, one expects to see K_L and K_S interference in the proper time distribution, as $2|\rho||\eta_{+-\gamma}|\, e^{-t/2\tau} \cos(\Delta m t+\phi_\rho+\phi_\eta)$. The proper time distribution for the $K_S \to \pi^+\pi^-\gamma$ in the regenerated beam is shown in Fig.4. A monte carlo simulation with and without interference term (let $\eta_{+-\gamma} = \eta_{+-}$) are superimposed on the data. Clearly the data favors the monte carlo with interference. A preliminary fitting result has shown

$$|\eta_{+-\gamma}| = 0.0020 \pm 0.0002(\text{stat}) \pm 0.0003\ (\text{syst}),$$

which is consistent with the world average of the CP-violation parameter $|\eta_{+-}| = (2.268 \pm .023)\times10^{-3}$ [12].

$K_L \to 3\pi^0$ QUADRATIC DECAY PARAMETER

The Dalitz plot parameters for the $K \to 3\pi$ decays can be parametrized by a series expansion as

$$|M|^2 \propto 1 + gY + \frac{g^2}{4}Y^2 + b(Y^2+\frac{X^2}{3}) + c(Y^2-\frac{X^2}{3}),$$

where $Y = (s_3-s_0)/m_\pi^2$ and $X = (s_2-s_1)/m_\pi^2$ are Dalitz variables [12]. In the $K_L \to 3\pi^0$ decay, the linear coefficient as well as the 1st and 3rd quadratic coefficients vanish, *i.e.* $g = 0$ and $c = 0$, because of the identical final state particles. The possible non-vanishing terms is then given by

$$|M_{000}|^2 \propto 1 + b(Y^2 + \frac{X^2}{3}).$$

Measurement on the $K_L \to 3\pi^0$ Dalitz plot has never been done before. Although the quadratic decay parameter b vanishes in the lowest order chiral perturbation theory, the combined fit for the $K^\pm \to 3\pi$ and $K_L \to \pi^+\pi^-\pi^0$ data by Devlin and Dickey [13] suggested an undesirable non-zero energy dependence $b = (-8.3 \pm 2.4)\times10^{-3}$, corresponding to a 2% drop from the center of Dalitz plot to the edge of the plot.

Based on a sample of 5M $K_L \to 3\pi^0$ decays in E731, we have performed an analysis on the $K_L \to 3\pi^0$ Dalitz distribution. Fig. 5 shows the data and a flat Dalitz monte carlo comparison of the event density distribution *vs* Dalitz angle Θ, where Θ is the angle between the event and Y-axis on the X-Y Dalitz plot. The good match between data and monte carlo gives us confidence on the proper reconstruction of the Dalitz variables in the $3\pi^0$ center of mass system. Fig. 6 shows the event density distribution *vs* R^2 for data and monte carlo, where $R^2 \equiv (Y^2 + X^2/3)$. The slope of the ratio of data *vs* monte carlo gives the direct measure of the quadratic decay parameter. The result is

$$b = (-0.6 \pm 1.4) \times 10^{-3}$$

with $\chi^2 = 36$ for 27 degrees of freedom, indicating a flat $3\pi^0$ Dalitz distribution.

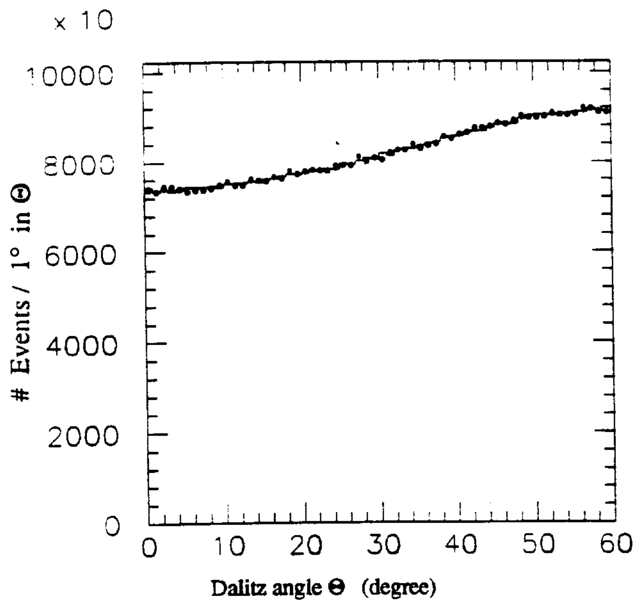

Fig. 5 Event density distribution in $K_L \to 3\pi^0$ Dalitz plot *vs* Dalitz angle Θ. Data with error bar were superimposed by a monte carlo with flat Dalitz distribution (dot).

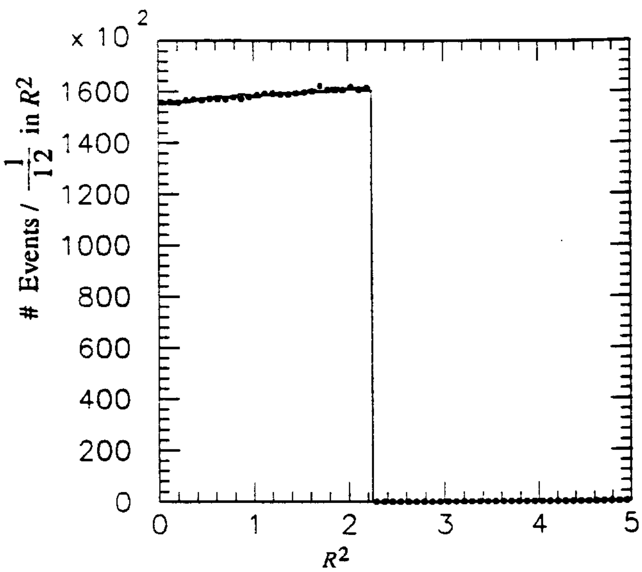

Fig. 6 Event density distribution for $K_L \to 3\pi^0$ *vs* R^2. Data were superimposed by a flat Dalitz monte carlo (dot).

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