The Fixed-Target Kaon Physics Program at Fermilab

A.R. Barker

Enrico Fermi Institute

University of Chicago, Chicago, IL 60637

ABSTRACT

The status of the measurement of ϵ'/ϵ by Fermilab E731 is reviewed. The preliminary result based on the full E731 data set is $\mathrm{Re}(\epsilon'/\epsilon) = (6.0 \pm 6.9) \times 10^{-4}$, where statistical and systematic errors have been combined in quadrature. Recently completed Kaon experiments E773 and E799-I are described, and estimates are given for the sensitivity of the measurements to be extracted from those data.

Status of Fermilab E-731; Measurement of Re(ϵ'/ϵ).

The two classic CP-Violating effects, the charge asymmetry in semileptonic K_L decays and the K_L–K_S interference in $\pi\pi$ decays, can both be explained on the basis of CP Violation in the K^0 mass matrix, parametrised by ϵ. This type of *indirect* CP Violation could be due to a Superweak interaction which at tree level couples states differing by two units of strangeness, such as the K^0 and $\overline{K}^0$. On the other hand, CP Violation can equally well be explained entirely within the context of the Standard Model with three generations. In the Wolfenstein parametrisation, the Cabbibo-Kobayashi-Maskawa (CKM) matrix can be written as

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where $\lambda \approx \sin\theta_C \approx 0.22$ and the current experimental estimate for A is 0.85 ± 0.09. The corrections to this equation are of order λ^4. If η is non-zero, CP-Violating effects should exist in the Standard Model; the observed value of ϵ is consistent with the range of values allowed by this Standard Model mechanism.

Standard Model CP-Violation is distinguished from that predicted by Superweak Models in that the tree-level interaction (W exchange) is a $\Delta S = 1$ coupling. Consequently, CP Violation should occur in the decay amplitudes as well as through the mass matrix. The most important contributions to this *direct* CP Violation in $K \to \pi\pi$ decays are the so-called Penguin diagrams, which are one-loop graphs where the loop consists of a W boson and an up-type quark, most importantly the top quark. For top quark masses less than about 100 GeV/c^2, the most important of these diagrams has the virtual t quark couple to a gluon and so describes the transition $s \to d\,g$. As M_t increases, Electroweak Penguins describing the transitions $s \to d\gamma^*$ and $s \to d\,Z^*$ become more important; these decrease the magnidude of the total decay amplitude and so suppress the rate of direct CP-Violating $\pi\pi$ decays.[1]

The rate of direct CP Violation in $K_L \to \pi\pi$ decays can be expressed in terms of the parameter ϵ', defined by the expression

$$\epsilon' \equiv \frac{i}{\sqrt{2}} e^{i(\delta_2-\delta_0)} \frac{\mathrm{Im}\, A_2}{A_0},$$

where δ_J is the $\pi\pi$ phase shift for a state of isospin J, and A_J is the weak transition amplitude between a K_L and a $\pi\pi$ state with isospin J. The CP-Violating decay amplitudes are normally expressed as ratios η_{+-} and η_{00} of the K_L matrix elements to the corresponding matrix elements for K_S decays. Experimentally, one measures the double ratio

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

Then $\mathrm{Re}(\epsilon'/\epsilon)$ can be derived from the relation $\mathrm{Re}(\epsilon'/\epsilon) = (R-1)/6$. Superweak models predict $R = 1$ and $\epsilon' = 0$. In E731, we want to measure very precisely the double-ratio R, to determine whether it differs slightly from unity. In order to do this, the experiment was carefully designed to minimize systematic biases. The technique chosen employed two parallel K_L beams. A B_4C regerator was placed in one of the beams, providing a flux of coherently regenerated K_S mesons. Downstream of the regenerator, most of the decays in one beam were K_S decays, and almost all of the decays in the other (vacuum) beam were K_L decays. The double ratio R was then measured by comparing the decay rates in the two beams.

This method of measuring R has the great advantage that K_L and K_S decays are detected at the same time, and by the same detector. Time-dependent changes in beam intensity or detector response thus affect K_L and K_S decays to the same final state at the same point in the decay volume in exactly the same way. In order to minimize biases that might arise as a result of differences between the two beams, the regenerator alternated from one beam to the other about once a minute. The detector consisted primarily of a system of four drift chambers and an analysing magnet for measuring charged particles' momenta together with an 804-block lead-glass calorimeter used to measure photon energies and to identify electrons by using E/p. A more complete description of the apparatus can be found in Ref. 2.

Because the lifetimes of the K_L and K_S are so dissimilar, the distribution of decay vertices in the vacuum beam is quite different from that observed in the regenerated beam. It is therefore necessary to simulate accurately the acceptance of the detector, which depends on z, the distance from the target to the decay vertex, in order to ensure that the effects of this non-uniform acceptance on R are correctly taken into account. We do this by using a Monte Carlo simulation to simulate and correct for the experimental acceptance. We try to understand the behaviour of the detector as far as possible from first principles; in doing so we rely heavily on large samples of K_{e3}, $K \to \pi^+\pi^-\pi^0$, and $K \to \pi^0\pi^0\pi^0$ events taken recorded simultaneously with the $K \to \pi\pi$ data. As an example of the accuracy of the simulation, Figure 1a compares the distribution of z values observed for $K \to \pi^0\pi^0\pi^0$ decays with the prediction of the Monte Carlo program; Figure 1b shows the Data/MC ratio.

Figure 2 shows mass distributions for all four $K_{L,S} \to \pi\pi$ decay modes. The statistics-limiting mode was formerly $K_L \to \pi^0\pi^0$. However, recently we have completed studies of detector response and backgrounds for neutral decays in the region between 137 and 150

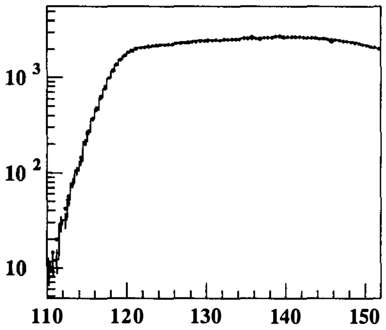

Fig. 1a) Pi0 Pi0 Decay Vertex (m)

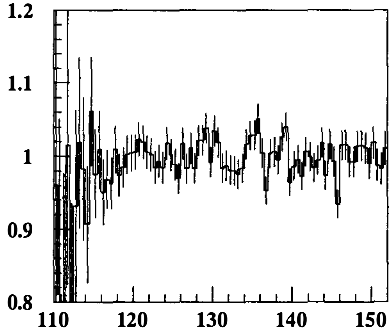

Fig. 1b) Data/Monte Carlo Ratio

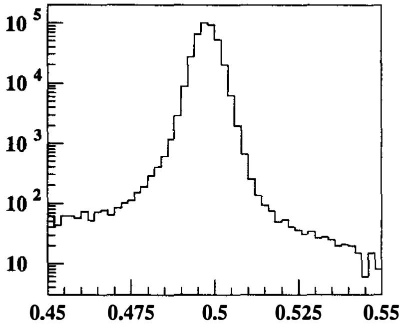

Fig. 2a) Pi+Pi- Mass, Vacuum Beam

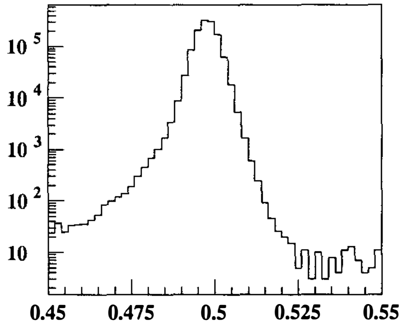

Fig. 2b) Pi+Pi- Mass, Regen. Beam

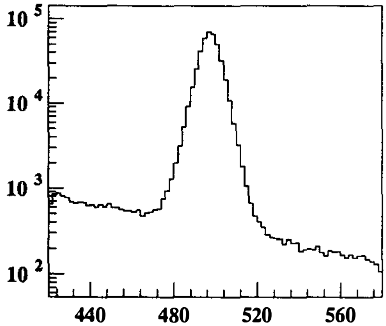

Fig. 2c) Pi0 Pi0 Mass, Vacuum Beam

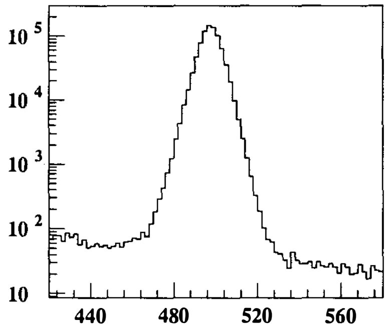

Fig. 2d) Pi0 Pi0 Mass, Regen. Beam

meters from the target. The use of $\pi^0\pi^0$ events in this region nearlys doubles our $K_L \to \pi^0\pi^0$ statistics, and the statistically limiting mode becomes $K_L \to \pi^+\pi^-$, where we have about 330,000 events, compared to about 440,000 in the neutral mode.

The backgrounds to the various $K \to \pi\pi$ decays are well understood. In the charged mode, the backgrounds arise from semileptonic decays with misidentified particles, and are negligible. In the neutral mode, the backgrounds seen in the mass histograms are mostly due to $\pi^0\pi^0\pi^0$ events with missing or fused photons. There is an additional background under the neutral K_L mass peak due to "crossover" events: these are events in which a K_S is regenerated diffractively with a transverse momentum which causes its reconstructed center-of-energy to be in the vacuum beam. We can accurately model this background by putting the transverse momentum distribution *measured* from charged K_S decays into the neutral Monte Carlo; the required subtraction turns out to be about 4% of the events in the mass peak.

After correcting for acceptance, the preliminary result from the full E731 data set (not yet including the downstream neutral events) is

$$\mathrm{Re}(\epsilon'/\epsilon) = (6.0 \pm 5.8\ [\mathrm{Stat.}] \pm 3.2\ [\mathrm{Syst.}] \pm 1.8\ [\mathrm{MC\ Stat.}]) \times 10^{-4}.$$

When a final result is announced later this year, the addition of the downstream neutral events will reduce the statistical error to about 5.1, and increased Monte Carlo statistics will eliminate the third error. Sources of systematic error include understanding of the lead-glass energy scale and resolution, corrections for accidental losses, background subtraction procedures, and uncertainties in acceptance corrections. The preliminary result is consistent both with Superweak models, and with recent Standard Model calculations of ϵ'/ϵ for top quark masses in the 150 – 200 GeV range currently favoured by LEP data. The same fit used to obtain $\mathrm{Re}(\epsilon'/\epsilon)$ from E731 data yields very precise values for τ_S and Δm. Our preliminary results for τ_S are $89.12 \pm 0.12 \pm 0.06$ ps (from $\pi^+\pi^-$ data) and $89.52 \pm 0.16 \pm 0.32$ ps (from $\pi^0\pi^0$ data), compared to the current Particle Data Group world average, 89.22 ± 0.20 ps.

A number of rare decay searches have also been conducted using E731 data. We have recently submitted a paper describing the results of a search for the rare decay $K_L \to \pi^0\nu\bar{\nu}$, using π^0 Dalitz decays. We look for events with missing transverse momentum greater than 140 MeV/c; seeing none, we set the first limit based on a direct search:

$$BR(K_L \to \pi^0\nu\bar{\nu}) < 2.2 \times 10^{-4} \text{ at the 90\% Confidence Level.}$$

E-773 and E-799 Phase I

Two experiments were conducted by our group during the 1991 fixed-target run at Fermilab. The first, E773, ran from July to September. This experiment was designed to measure the difference between the phases of η_{00} and η_{+-}. If these differ by more than about 0.2°, then CPT symmetry is violated. The experiment used the same beam and detector as E731, with a few changes. Regenerators were placed in both beams, at different z locations. The regenerators were constructed entirely from scintillator; this fully active design enabled us to drastically reduce backgrounds from diffractive and inelastic regeneration. A new trigger processor was added, which enabled us to take charged decays occurring as far downstream as the first drift chamber, a decay region 22 meters longer than in E731. The scintillator hodoscope which cut across the vacuum decay volume and defined the dowstream end of the E731 charged acceptance was removed from the detector. Some 475 million triggers were recorded during the run. The first production pass on E773 data was completed in March, 1992; about 2.3 million $\pi^+\pi^-$ events were reconstructed, as well as 430,000 $\pi^0\pi^0$ events. We expect ultimately to measure $\phi_{00} - \phi_{+-}$ to a statistical precision of about 0.35° from these data.

For the second half of the recent run, the detector was modified again, for another new experiment, called E799. This experiment is a two-phase search for rare K_L decays, especially $K_L \to \pi^0 e^+ e^-$. To run Phase I of E799, both regenerators were removed from the apparatus. The beam sizes were increased, and Be absorber which had been in place for both E731 and E773 was removed in order to further increase the kaon intensity. A new trigger processor was installed which measured the charged multiplicity in the drift chambers. About 20% of the run was devoted to a $K_L \to \pi^0\gamma\gamma$ search using a lead/scintillating-fiber preshower detector installed in front of the lead-glass calorimeter.

A variety of triggers were defined in order to allow us to search for a number of different rare decays. Between November and January, 1992, about 485 million events were recorded. Using the same trigger as will be used to search for $K_L \to \pi^0 e^+ e^-$, we have reconstructed several hundred thousand $K_L \to \pi^0\pi^0\pi^0$ events with π^0 Dalitz decays. Based on the number of events found in this channel, we estimate our single-event sensitivity for $K_L \to \pi^0 e^+ e^-$ will be approximately 8×10^{-10}.

REFERENCES

1) G. Buchalla, A.J. Buras, and M.K. Harlander, Nucl. Phys. **B337,** 313 (1990).

2) J.R. Patterson *et al.*, Phys. Rev. Lett. **64,** 1491 (1990); see also E.C. Swallow, in *Proc. of the APS Div. of Particles and Fields Mtg.*, Vancouver, B.C., August 1991.