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Determination of Re(ϵ'/ϵ) by the Simultaneous Detection of the Four $K_{L,S} \rightarrow \pi\pi$ Decay Modes

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The E731 experiment at Fermilab has searched for direct *CP* violation in $K^0 \rightarrow \pi\pi$, which is parametrized by ϵ'/ϵ. For the first time all four of the $K_{L,S} \rightarrow \pi\pi$ modes were collected simultaneously, which greatly facilitated studies of systematic uncertainty. We find $\text{Re}(\epsilon'/\epsilon) = -0.0004 \pm 0.0014(\text{stat}) \pm 0.0006(\text{syst})$. The result provides no evidence for direct *CP* violation.

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This paper presents a new determination of the *CP*-violation parameter Re(ϵ'/ϵ). Since a result[1] from the first run of this experiment was reported, the detector has been improved and substantially more data have been collected.

The six-quark model[2] of Cabibbo, Kobayashi, and Maskawa (CKM) provides the most natural way of incorporating *CP* violation into the weak interaction. Until very recently, the only observed *CP*-nonconserving effects were consistent with asymmetric K^0-$\bar{K}^0$ mixing, parametrized by ϵ. This is a second-order effect in the CKM framework, but could also signal a new $\Delta S = 2$ interaction (e.g., superweak[3]). Within the CKM framework, first-order ("direct") *CP* nonconservation in $K^0 \rightarrow \pi\pi$ decays, parametrized by ϵ'/ϵ, is also expected, and searches for it in the predicted range provide an important test of the model. Recently, the NA31 group at CERN reported[4] evidence for such an effect.

As is well known, Re(ϵ'/ϵ) can be determined from the double ratio R of the $\pi\pi$ decay rates of the K_L and K_S mesons:

$$R \equiv \frac{\Gamma(K_S \rightarrow \pi^+\pi^-)/\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow \pi^0\pi^0)/\Gamma(K_L \rightarrow \pi^0\pi^0)} \approx 1 - 6\,\text{Re}(\epsilon'/\epsilon)\,.$$

It is important to minimize systematic uncertainty in the collection and analysis of the four decay modes. In our experiment, the K_S are provided by coherent regeneration, ensuring an angular divergence identical to that of the K_L, and very similar momentum spectra for $\pi\pi$ events. Decays of K_S and K_L to a given final state (charged or neutral) are collected at the same time by means of side-by-side K_L and K_S beams, so electronic drifts, accelerator instabilities, and phototube gain shifts affect them virtually identically. Furthermore, the regenerator alternates between the beams, rendering the effect of asymmetries in the beams or the detector response negligible. The analysis[5] reported here is based on about 20% of the data collected during a fixed-target run at Fermi National Accelerator Laboratory. These are distinguished in that, for the first time, decays from all four modes were collected simultaneously.

As a function of proper time t from the regenerator, the $\pi\pi$ decay rates in the vacuum and regenerated beams are proportional to $|\eta|^2$ and $|\rho \exp(-t/2\tau_S + i\Delta m t) + \eta|^2$, respectively; ρ is the coherent regeneration amplitude, τ_S is the K_S lifetime, Δm is the K_L-K_S mass difference, and η is the appropriate ratio of K_L-to-K_S decay amplitudes. Because $|\rho| \gg |\eta|$, the ratio of the total number of regenerated to vacuum charged (neutral) decays $R_{+-(00)}$ is proportional to $|\rho/\eta_{+-(00)}|^2$. Thus, $R \approx R_{+-}/R_{00}$.

Kaons were produced by 800-GeV protons incident at 5 mrad on a beryllium target. The regenerator, instrumented to detect inelastic regeneration, was located 123 m downstream of the target.

An 804-block lead-glass calorimeter 181 m from the target determined the energies and positions of photons and electrons. Its energy resolution was roughly 1.5%

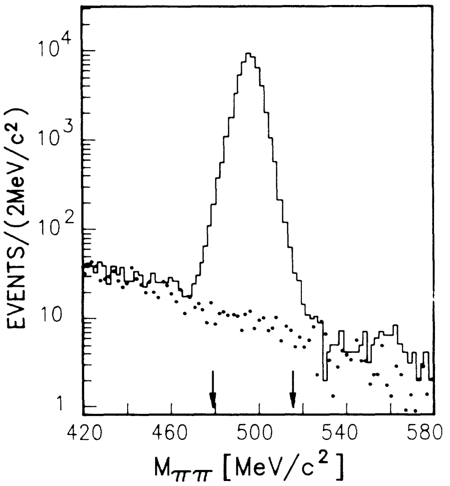

FIG. 1. Invariant-mass distribution for $K_L \to \pi^0\pi^0$ events. The histogram is data; the solid circles are from a Monte Carlo simulation for the residual $K_L \to \pi^0\pi^0\pi^0$ background, absolutely normalized. A very small nonkaon contribution, seen here at high mass, is also subtracted. The arrows indicate the positions of the cuts.

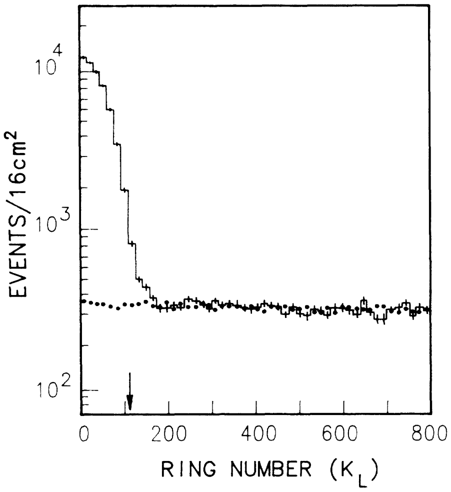

FIG. 2. Event density in equal-area concentric rings around the K_L beam for $\pi^0\pi^0$ events. The histogram is data; the solid circles show the expected size and shape of incoherent events from the regenerator as determined from $\pi^+\pi^-$. The arrow indicates the position of the cut.

$(2.5\%)+5\%/\sqrt{E}$ (E in GeV) for electrons (photons). The neutral trigger required greater than 28 GeV in the calorimeter and either four or six isolated electromagnetic clusters,[6] accepting $\pi^0\pi^0\pi^0$ as well as $\pi^0\pi^0$ decays. Eleven planes of photon veto counters were employed to reduce background from $\pi^0\pi^0\pi^0$ decays with photons missing the lead glass.

The decay vertex for $K_{L,S} \to \pi^0\pi^0$ decays was found by pairing the photons using the known π^0 mass as a constraint. The $\pi^0\pi^0$ invariant mass is shown in Fig. 1 for K_L decays, differentiated from K_S decays by means of the center of energy of the four photons in the calorimeter. The residual background from $K_L \to \pi^0\pi^0\pi^0$ decays was $(0.37 \pm 0.07)\%$, and was well reproduced by a Monte Carlo simulation.

Charged tracks were reconstructed (typically with 1% momentum resolution) using a 16-plane drift-chamber spectrometer with 100-μm resolution per plane. A (prescaled) two-track trigger was formed using hodoscopes at 137.8 and 179.5 m; $K_{\mu 3}$ decays were rejected using a muon filter. Thus, $\pi e \nu$ and $\pi^+\pi^-\pi^0$ as well as $\pi^+\pi^-$ decays were accepted.

For $K_{L,S} \to \pi^+\pi^-$ decays the invariant-mass resolution was about 3.5 MeV/c^2; the cut was ± 14 MeV/c^2 around the nominal kaon mass. Background from $\pi e \nu$ decays was reduced with cuts on E/p and the kaon transverse momentum ($P_t^2 < 250$ MeV^2/c^2). The residual K_L background was $(0.32 \pm 0.06)\%$.

To extract the coherently regenerated K_S signals, the diffractive and inelastic contributions must be subtracted. After the P_t^2 cut, we found a $(0.13 \pm 0.01)\%$ contribution to $K_S \to \pi^+\pi^-$ from such incoherent events; this is 2.3 times smaller than in Ref. 1, largely because of the removal of 1.5 in. of lead from the regenerator. For neutral decays, only the center of energy at the calorimeter was available to identify incoherently regenerated K_S, which scattered into both the K_L and K_S beams. Their contributions were accurately predicted from the P_t^2 distribution for simultaneously observed $\pi^+\pi^-$ decays (Fig. 2), and were $[4.70 \pm 0.14(\text{syst})]\%$ and $[2.56 \pm 0.07(\text{syst})]\%$ for the K_L and K_S samples, respectively.

Acceptance corrections, necessary because of the difference in K_S and K_L vertex distributions, were made using a detailed Monte Carlo simulation of the beam and detector. The nonlinear and non-Gaussian response of the lead glass to photons, important for neutral decays, was reproduced with no free parameters, using results from EGS[7] simulations of electromagnetic showers together with the effective attenuation length of Cherenkov light in each block. The restriction that the *same* detector and beam parameters be used in the simulation of all four modes, applicable since all were collected simultaneously, provided a powerful check of the Monte Carlo simulation as a whole.

The $K_L \to \pi^+\pi^-$ decay-vertex distribution is well reproduced by a Monte Carlo simulation, as shown in Fig. 3. The agreement is equally good for the other decays.

The final sample included kaons with energy between 40 and 150 GeV decaying in the region from 120 to 137 m from the target. The raw numbers of events passing all cuts and the background and acceptance corrections are given in Table I with the value of R_{+-}/R_{00} at each stage. The acceptance was similar for K_S and K_L: It

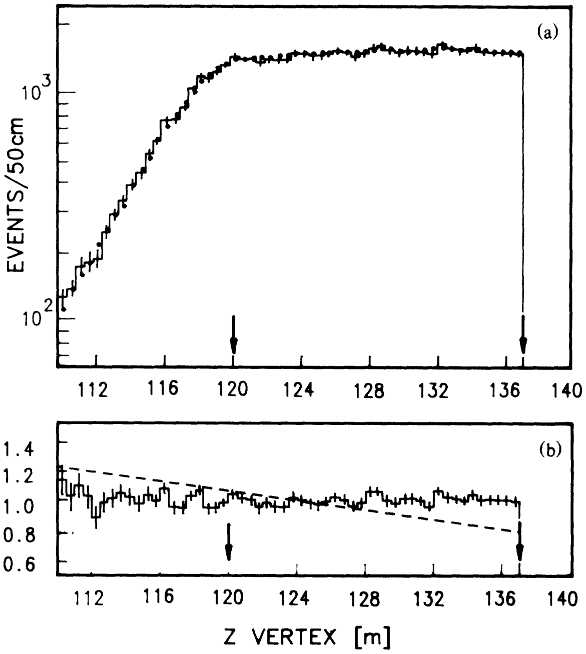

FIG. 3. (a) Decay-vertex distribution for $K_L \to \pi^+\pi^-$ events. The histogram is data and the solid circles are from a Monte Carlo simulation. (b) Ratio of data to a Monte Carlo simulation. The dashed line corresponds to an acceptance error that would shift the K_S-to-K_L ratio by 2%, the size of the NA31 effect. The arrows indicate the positions of the cuts.

varied slowly with decay vertex, the mean of which differed for K_S and K_L decays by less than 1.5 m. The total change in the double ratio from raw data to final acceptance-corrected samples is 7%; the final double ratio indicates a small value of $\mathrm{Re}(\epsilon'/\epsilon)$.

To extract $\mathrm{Re}(\epsilon'/\epsilon)$, we fit R_{+-} and R_{00} for $|\rho/\eta|$ in the two modes in 10-GeV/c bins of kaon momentum. The momentum dependence, common to the neutral and charged modes, is expected to obey a power law,[8] while a magnitude difference is proportional to $\mathrm{Re}(\epsilon'/\epsilon)$. The best-fit power for the charged (neutral) mode was -0.602 ± 0.010 (-0.605 ± 0.010) with $\chi^2 = 11.5$ (10.7) for nine degrees of freedom; the two are consistent with each other and with previous determinations.[9] The combined fit yielded $\mathrm{Re}(\epsilon'/\epsilon) = -0.0004 \pm 0.0014$ (stat).

TABLE I. Event totals and corrections.

	Neutral	Charged	R_{+-}/R_{00}
Raw events			
K_L	52 226	43 357	
K_S	201 332	178 803	1.0698
Background fractions			
K_L	0.0507	0.0032	
K_S	0.0256	0.0013	1.0442
Acceptance			
K_L	0.1884	0.5041	
K_S	0.1813	0.5064	1.0003

Systematic errors were associated with background subtractions, detector and beam variations with time, accidental activity in the detector, energy calibration and resolution, and acceptance.

Uncertainty in the backgrounds is dominated by those in the incoherent contributions to neutral decays, which are expected to partially cancel in R_{00}. As a conservative estimate of the total uncertainty on the double ratio all background errors are added in quadrature, yielding a total of 0.18%.

All decays to a common final state were analyzed together; this and the use of loose cuts (the reconstruction efficiency was more than 90% for all $\pi\pi$ decays satisfying the geometrical requirements) reduced sensitivity to time variations: R_{+-} and R_{00} were stable throughout even though the intensity, targeting, and detector efficiencies varied.

Accidental activity, concentrated near the vacuum beam, could have changed the relative K_L and K_S efficiencies. Accidental events, collected with the $\pi\pi$ data at a rate proportional to the instantaneous beam intensity, contained a photon cluster 2.7% of the time and an average of 8.5 chamber hits. When overlaid on $\pi\pi$ Monte Carlo events they correctly reproduced the small intensity dependence of our selection criteria; however, no bias between K_L and K_S was seen within the statistical error of the simulation (0.07%) for either mode.

The energy scale for the charged mode was determined sufficiently accurately using the known K^0 and Λ masses. For the neutral mode, after electron calibration of the individual lead-glass blocks, the overall scale was adjusted ($\approx 0.5\%$) using the sharp edge in the K_S decay vertex at the regenerator, leaving a residual uncertainty of 0.1%. By choice of the fiducial region,[10] this resulted in only 0.03% uncertainty in R_{00}. Uncertainty in the energy resolution, however, led to an 0.2% uncertainty in R_{00}.

Acceptances were extensively studied using 10^7 $\pi e \nu$ and 6×10^6 $\pi^0\pi^0\pi^0$ decays taken with the $\pi\pi$ events; the agreement in vertex and other distributions with Monte Carlo simulation over the chosen fiducial region was excellent. Also, when $\mathrm{Re}(\epsilon'/\epsilon)$ was extracted using small vertex bins, almost eliminating the need for acceptance corrections, a consistent result was obtained (with increased systematic error from resolution uncertainty).

In the same analysis, we fit[11] for τ_S and Δm. Separate neutral and charged fits were consistent and the combined results were $\tau_S = [0.8902 \pm 0.0021(\mathrm{stat})] \times 10^{-10}$ sec and $\Delta m = [0.534 \pm 0.009(\mathrm{stat})] \times 10^{10} \hbar$ sec^{-1}, in agreement with the accepted values.[12] These studies, together with the stability of R_{+-} and R_{00} when selection criteria, beam profiles, and detector apertures and efficiencies were varied in the Monte Carlo simulation, led to the assignment of 0.25% systematic uncertainty due to acceptance.

Combining these uncertainties in quadrature, the total systematic error on the double ratio is then 0.38%. The final result is

$$\mathrm{Re}(\epsilon'/\epsilon) = -0.0004 \pm 0.0014(\mathrm{stat}) \pm 0.0006(\mathrm{syst}).$$

The accurate determinations of τ_S, Δm, and the regeneration momentum dependence for both modes attest to the soundness of the technique.

The result is consistent with the superweak model;[3] it does not confirm recent evidence[4] for direct *CP* violation. The CKM standard model may also account for such a small value of $\mathrm{Re}(\epsilon'/\epsilon)$ with a heavy top quark[13] or with the incorporation of electroweak corrections which could be important.[14]

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[10] When the γ energies are decreased, approximately the same number of K_L leave at the downstream boundary as enter at the upstream boundary; essentially all K_S are included.

[11] The *CPT*-violating phase difference ($\Delta\Phi$) between η_{+-} and η_{00} was also fit and found consistent with zero [M. Karlsson *et al.* (unpublished)]. Here we assume $\Delta\Phi = 0$.

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