New Measurement of the *CP* Violation Parameter $\eta_{+-\gamma}$

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We have measured the *CP* violation parameter $\eta_{+-\gamma}$ in a neutral kaon experiment, E773, at Fermilab. This parameter characterizes *CP* violation in the decay $K_L \to \pi^+\pi^-\gamma$. Kaon decays into $\pi^+\pi^-$ collected simultaneously were used for normalization. Our result is $|\eta_{+-\gamma}| = [2.359 \pm 0.062(\text{stat}) \pm 0.040(\text{syst})] \times 10^{-3}$ with a phase $\phi_{+-\gamma} = [43.8 \pm 3.5(\text{stat}) \pm 1.9(\text{syst})]^\circ$. The prediction that $\eta_{+-\gamma}$ should be very close to η_{+-} is supported by our result.

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The discovery of *CP* symmetry nonconservation in the weak interaction came in 1964 when the decay $K_L^0 \to \pi^+\pi^-$ was found [1]. Within three years, the *CP*-violating decay $K_L^0 \to \pi^0\pi^0$ was identified, as was a *CP*-violating charge asymmetry in the $K_L^0 \to \pi e \nu$ and $\pi\mu\nu$ decays [2–4]. In the subsequent time, only one additional such decay has been found: In 1993 interference between K_S^0 and K_L^0 was observed in $K^0 \to \pi^+\pi^-\gamma$ decays by Fermilab E731 [5], proving that *CP* is violated here as well. Almost all previous measurements of *CP*-violating amplitudes are consistent with the model that *CP* violation occurs only in the $K^0/\overline{K^0}$ mass matrix and is described by one complex parameter ϵ of magnitude $\sim 2.3 \times 10^{-3}$ and phase $\sim 43^\circ$ [6]. It is important to determine if the $\pi^+\pi^-\gamma$ decay fits into this picture as well. The 1993 measurement was consistent with this picture within uncertainties, however, these uncertainties were relatively large when compared to the current understanding of the $\pi^+\pi^-$ decay. The theoretical expectation is that any difference between the *CP* violation parameter describing this decay, $\eta_{+-\gamma}$, and $\eta_{+-} \approx \epsilon$ should be very small [7]. In this Letter, we report a new, more precise measurement of the $\pi^+\pi^-\gamma$ decay amplitude.

There are two processes which contribute to the $\pi^+\pi^-\gamma$ decay amplitude: inner bremsstrahlung (IB) and direct emission (DE). The K_S^0 decay is dominated by the IB process where there is a $K_S^0 \to \pi^+\pi^-$ decay with a photon radiated by one of the final-state pions. For the K_L^0 decay, this process is suppressed (because the underlying $\pi^+\pi^-$ decay violates *CP* symmetry) thereby allowing the observation of the DE process where the photon comes from the primary decay vertex. Previous experiments have found that the spectrum of photon energies in the kaon center of mass frame fits an electric dipole ($E1$) form for the IB term and a magnetic dipole ($M1$) form, modified for the effects of vector meson intermediaries, for the DE term [8–10]. The fact that the IB and DE components have different photon energy spectra allows one to determine the ratio of their contribution to the K_L^0 decay rate: r = (DE rate)/(IB rate) [9–11]. Finally, the $E1$ term for the K_S^0 (K_L^0) is *CP* conserving (violating) and the modified $M1$ term for the K_L^0 is *CP* conserving.

Since the terms in the multipole expansion of each decay amplitude are orthogonal, interference between K_S^0 and K_L^0 will occur only for like-term multipoles. The principal contribution to the interference comes from the two IB $E1$ decays; however, higher-order multipoles contribute if present. In addition, although direct *CP* violation is expected to be small, it could present itself through a DE $E1$ transition of the K_L^0 interfering with the IB $E1$ transition

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of the K_S^0. Therefore, what one measures is the ratio of decay amplitudes:

$$\eta_{+-\gamma} = \frac{A(K_L \to \pi^+\pi^-\gamma, CP \text{ violating})}{A(K_S \to \pi^+\pi^-\gamma)}\,. \tag{1}$$

In the present experiment, we used the phenomenon of coherent regeneration to study the interference between the K_L and K_S decay amplitudes. As a K_L beam passes through material, the $K^0/\overline{K^0}$ mixture is altered, causing K_S mesons to appear in the beam. The number of $\pi^+\pi^-\gamma$ decays per unit proper time observed downstream of the regenerator is

$$\frac{dN}{d\tau} = \frac{N_S B_{+-\gamma}}{|\rho|^2\tau_S}\{|\rho|^2 e^{-\tau/\tau_S} + |\eta_{+-\gamma}|^2 e^{-\tau/\tau_L}(1+r) + 2|\rho||\eta_{+-\gamma}|\cos(\Delta m\tau + \phi_\rho - \phi_\eta)e^{-\tau(1/\tau_S + 1/\tau_L)/2}\}, \tag{2}$$

where N_S is the number of regenerated K_S, $B_{+-\gamma}$ is the $K_S \to \pi^+\pi^-\gamma$ branching ratio, τ_S (τ_L) is the K_S (K_L) lifetime, and Δm is the $K_L - K_S$ mass difference. The complex parameter ρ, called the regeneration amplitude, is the ratio of coherently regenerated K_S to transmitted K_L amplitudes and ϕ_ρ (ϕ_η) is the phase of ρ ($\eta_{+-\gamma}$).

The results quoted here come from Fermilab experiment 773, which was performed in the Meson Center beam line. Two nearly parallel K_L beams were produced from an 800 GeV/c primary proton beam striking a beryllium target. The K_L beams themselves were incident on our apparatus which consisted of a pair of regenerators and an evacuated decay vessel followed by a magnetic spectrometer and a lead glass electromagnetic calorimeter as shown in Fig. 1.

The upstream regenerator was 1.2 interaction lengths long and was 11.28 m upstream of the shorter (0.4 interaction length) downstream regenerator. The two regenerators were composed of scintillator and instrumented with photomultiplier tubes for vetoing events in which the kaon underwent inelastic scattering within the regenerator or where the decay occurred before the downstream end of the regenerator. The regenerators were alternated between the two beams between spills to reduce systematic errors.

The spectrometer consisted of four drift chambers, two in front of and two behind the analyzing magnet. The magnet provided a transverse momentum kick of 200 MeV/c. Each chamber contained two horizontal and two vertical planes of wires with position resolution 80–100 μm, yielding a momentum resolution of $\sigma_p/p = 0.45[1 \oplus p/(40 \text{ GeV}/c)]\%$. The calorimeter was a circular array of 804 lead glass blocks, each 5.81×5.81 cm^2 in cross section and 18.7 radiation lengths deep, with a photon energy resolution which varied from 3% to 6% depending on photon energy and location. A more detailed description of the apparatus may be found elsewhere [12].

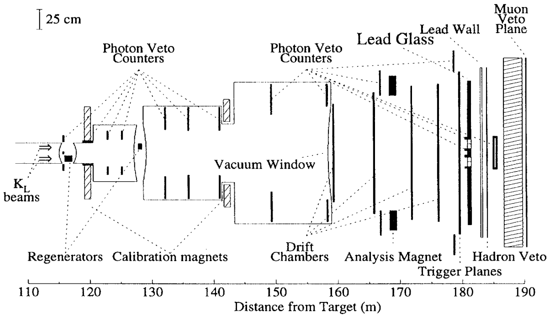

FIG. 1. Schematic of the FNAL E773 detector.

The trigger demanded that two oppositely charged particles traverse the detector by requiring that there be one track on either side of the horizontal and vertical midplanes of two scintillator hodoscopes downstream of the spectrometer magnet and chambers. Events were vetoed if charged particles struck any of the annular veto counters at various stations along the edges of the vacuum vessel or if there was a hit in the muon veto plane. In addition, we required there be a hit in a pair of trigger hodoscopes at 141 m. Approximately half way through the run, these planes were removed (thereby increasing the length of the decay volume) and their function in the trigger was replaced by new demands on the pattern of hits in the drift chambers. No requirement was made on information contained in the lead glass calorimeter.

The data were divided into four sets (according to which regenerator the kaon traversed and whether the hodoscope at 141 m had been removed) which were analyzed independently. In the $\pi^+\pi^-\gamma$ analysis, each event was required to have two tracks in the spectrometer coincidental with at least one cluster in the calorimeter with an energy greater than 1.5 GeV, not associated with a charged track. This photon was required to have an energy greater than 20 MeV in the kaon center of mass. To select coherently regenerated $\pi^+\pi^-\gamma$ decays, the reconstructed $\pi^+\pi^-\gamma$ invariant mass ($M_{+-\gamma}$) had to be between 484 and 512 MeV/c^2 and the square of the measured momentum component transverse to the incident kaon's direction (P_T^2) was required to be less than 150 (MeV/c)^2. In addition, fiducial requirements were imposed.

To eliminate $\pi\mu\nu$ decays, each track was required to have a momentum of at least 7 GeV/c and to project to a point within the acceptance of the muon hodoscope. This assured that if the particle were a muon, it would have had a high probability of surviving the 3 m steel muon filter and leaving a hit in the hodoscope. $\pi e\nu$ decays were excluded by demanding that for each charged particle the ratio of energy measured in the lead glass calorimeter to momentum measured in the spectrometer, E/p, be less than 0.85. To remove $\Lambda \rightarrow p\pi$ decays, if the reconstructed $p\pi$ invariant mass was within 6 MeV/c^2 of the Λ mass, we rejected events with a p/π momentum ratio greater than 3 and a Λ momentum greater than 100 GeV/c. To suppress background from $\pi^+\pi^-\pi^0$ decays, a cut was made on the variable

$$P^2_{\pi^0} = \frac{(M_K^2 - M_{\pi^0}^2 - M_c^2)^2 - 4M_{\pi^0}^2 M_c^2 - 4M_K^2 (P_T^2)_c}{4[(P_T^2)_c + M_c^2]},$$

where M_c is the invariant mass of the two charged tracks and $(P_T^2)_c$ is their transverse momentum with respect to the parent kaon [13]. Events with $P^2_{\pi^0} > -0.011$ (GeV/c)^2 were eliminated. Decays to $\pi^+\pi^-$ were removed by eliminating events with a reconstructed $\pi^+\pi^-$ invariant mass greater than 484 MeV/c^2. After analysis 9045 events survived, 77% of which came from the upstream regenerator.

The detector acceptance was calculated by the Monte Carlo method. The simulation included the geometry of the beams and detector elements, the efficiency and resolution of each detector element, and the known properties of kaon regeneration and decays. Figure 2 shows four histograms, typical of many, which demonstrate that the features of the data are accurately reproduced by the Monte Carlo simulation. The average overall acceptance of our detector was 14.6% (9.2%) for IB (DE) decays.

In Fig. 3 we show the decay probability for $K \rightarrow \pi^+\pi^-\gamma$ as a function of proper time, as determined from the data, and as predicted from Eq. (2). To demonstrate the effect of interference, we also show the prediction of Eq. (2) if there were no interference between the K_L and K_S amplitudes in this decay. It is clear that our data require the presence of K_L-K_S interference.

The selected events for each set were put into p vs z distributions (z being the longitudinal distance of the decay vertex from the target) in 10 GeV/c × 2 m bins for fitting. The background (which included scattered, noncoherent, $K \rightarrow \pi^+\pi^-\gamma$ as well as non-$\pi\pi\gamma$ decays) was then subtracted from each (p, z) bin. To estimate the total number of background events, a fit was performed to the distribution of events in the $M_{+-\gamma}$ vs P_T^2 plane. The fit excluded the signal region and we interpolated to estimate the background. For the upstream (downstream) regenerator the background was 2.3% (2.5%) of the total. Events near, but outside of, the signal region were used to provide the p-z distribution of background events. The p-z distribution found from events to the left and right of the signal box in $M_{+-\gamma}$ was similar to the distribution of events at high P_T^2. The fit to the data was insensitive to the details of the background subtraction.

We performed a fit of the data to the hypothesis of $D(p,z) = S(p) \cdot f(p,z) \cdot A(p,z)$, where $S(p)$ is the momentum spectrum of kaons exiting the regenerator, $f(p,z)$ is the integral of Eq. (2) over the (p,z) bin, and $A(p,z)$ is the acceptance of the detector as calculated from our Monte Carlo simulation. We determined $S(p)$ from the $\pi^+\pi^-$ data. By using the data, we find not only the shape of the spectrum, but also the absolute normalization (thereby accounting for N_S). The $\pi^+\pi^-$ events used the same trigger as the $\pi^+\pi^-\gamma$ data and were collected simultaneously. The analysis of the $\pi^+\pi^-$ data used many of the same cuts as the $\pi^+\pi^-\gamma$ analysis and has been described in detail elsewhere [12].

E731 had separate K_S and K_L beams which were used to measure $B_{+-\gamma}$ and r. In our fit, we constrained $B_{+-\gamma}$ and r within their uncertainties to these values [9]. Our $\pi^+\pi^-$ data were used to determine ρ and ϕ_{+-}, while the Δm used was the combined E731/E773 value [14]. The magnitudes of τ_L, τ_S, and $|\eta_{+-}|$ used were the Particle Data Group averages [15]. All four subsets were fit separately and checked for consistency before combining all data into one overall fit. The result of a maximum-likelihood fit to all four data sets is

$$|\eta_{+-\gamma}| = (2.359 \pm 0.062) \times 10^{-3},$$

$$\phi_{+-\gamma} = (43.8 \pm 3.5)^\circ.$$

This fit had a χ^2 of 350 for 315 degrees of freedom [16].

We estimated our systematic uncertainties by varying many different elements of our analysis and observing the effect on the fit for $|\eta_{+-\gamma}|$ and $\phi_{+-\gamma}$. The result for $|\eta_{+-\gamma}|$ is $\pm 0.040 \times 10^{-3}$. The largest contributions

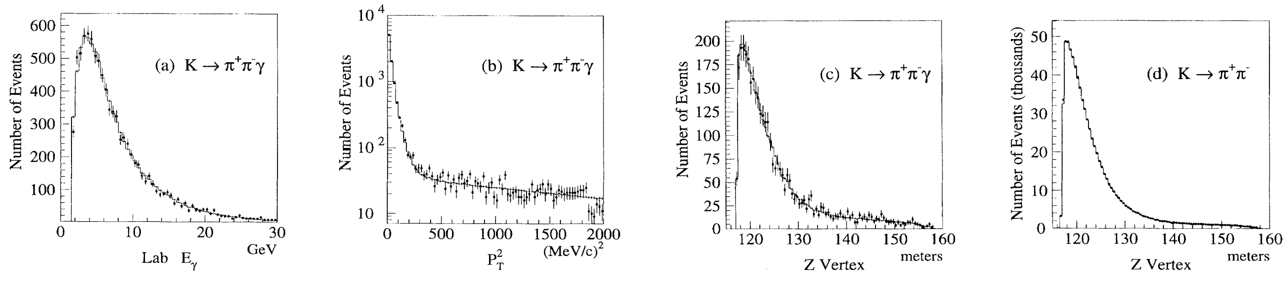

FIG. 2. Data: Monte Carlo comparisons for $K \rightarrow \pi^+\pi^-\gamma$ and $K \rightarrow \pi^+\pi^-$. Energy of the photon, transverse momentum, and longitudinal decay vertex are shown. The data are represented by the dots, while the Monte Carlo distribution is the histogram. For (a) and (b), all data sets are included, while for (c) and (d) only a subset of data from the upstream regenerator is shown. In (b), the measured background distribution, as determined from data, was added to the Monte Carlo P_T^2 distribution.

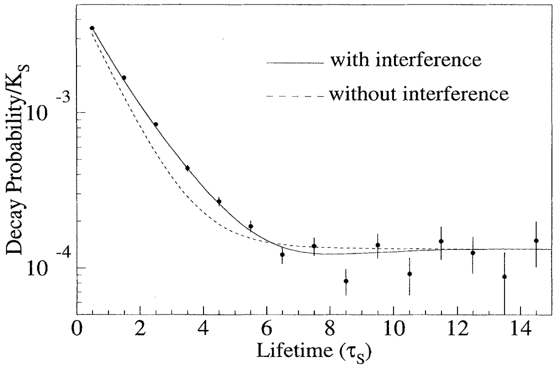

FIG. 3. The decay probability for $K \rightarrow \pi^+\pi^-\gamma$ as a function of proper time. The vertical scale is the absolutely normalized decay probability per K_S exiting the regenerator. The horizontal scale is in units of K_S lifetimes (τ_s). The data (corrected for acceptance and with background subtracted as described in the text) from the upstream regenerator are represented by the dots (statistical error bars are shown). The solid line shows the prediction of Eq. (2) resulting from the fit (see text), whereas the dashed line is the prediction if there were no interference between K_L and K_S.

come from the uncertainties in background shape, flux normalization, and $|\eta_{+-}|$. These contribute 0.030, 0.021, and 0.013 (each $\times 10^{-3}$), respectively. The systematic uncertainty in $\phi_{+-\gamma}$ is $\pm 1.9°$ and is dominated by the uncertainties in normalization, ρ, and $|\eta_{+-}|$, which contribute 1.2°, 0.9°, and 0.9° respectively.

In summary, we have observed the interference between coherently regenerated K_S and transmitted K_L mesons decaying to the $\pi^+\pi^-\gamma$ final state. We collected 8836 of these decays (with a background of 209 events) and fit their distribution in p and z to obtain precise values for the magnitude and phase of $\eta_{+-\gamma}$. Our result is, within uncertainties, equal to η_{+-} (in both magnitude and phase) [12,15] and is consistent with the prediction that any direct CP-violating contribution to $\eta_{+-\gamma}$ must be very small.

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[14] For completeness, we include the values used (see [12] above). $\rho \propto (f - \bar{f})/k$ which follows a power law in kaon momentum. Using the $\pi^+\pi^-$ data to fit a single combined (carbon + hydrogen) power law for our regenerators ($CH_{1.1}$), we find $|(f - \bar{f})/k| = 1.302 \pm 0.006$ mb at 70 GeV/c and it varies as $p^{-0.574 \pm 0.007}$. We also find $\phi_{+-} = 43.53°$ and $\Delta m = 0.5282 \times 10^{10} \hbar\, s^{-1}$.

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[16] As a consistency check, we fixed $|\eta_{+-\gamma}|$ and $\phi_{+-\gamma}$ to our measured values and constrained r to the value from [9]. Refitting the data, we find $B_{+-\gamma} = [4.71 \pm 0.05(\text{stat})] \times 10^{-3}$.