Measurement of the CP-Violation Parameter $\eta_{+-\gamma}$ in Neutral Kaon Decays

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Interference between K_S and K_L decays into the final state $\pi^+\pi^-\gamma$ has been observed in experiment 731 at Fermilab. By fitting the distribution of decays downstream of a regenerator, a new CP-violation parameter $\eta_{+-\gamma}$, analogous to η_{+-}, has been measured, with its magnitude equal to $(2.15\pm0.26\pm0.20)\times10^{-3}$, and $\phi_{+-\gamma}$, the associated phase angle, equal to $(72\pm23\pm17)°$. Assuming that any difference between this fit value for $\eta_{+-\gamma}$ and the previously measured value for η_{+-} can be attributed to direct CP violation in this decay, a limit of $|\epsilon'_{+-\gamma}|/\epsilon<0.3$ at the 90% confidence level has been made.

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Decays of the neutral kaons, K_L^0 and K_S^0, have been studied in great detail because they represent the only known example of a system that exhibits violation of CP symmetry. A demonstration of this symmetry violation is the fact that the K_L^0 can decay into both CP-odd and CP-even final states [1]. Because mixing can occur in the neutral kaon system, it is possible to see an interference pattern in the proper time distribution of its decays [2]. We report here the first observation of K_L-K_S interference for the decay into the final state $\pi^+\pi^-\gamma$, and our measurement of the level of CP violation in this decay. By comparing the magnitude of the observed CP violation to that of the $\pi^+\pi^-$ decay mode, a limit for the amount of direct CP violation in the decay has been obtained.

The two electroweak eigenstates of neutral kaons can be described as

$$K_L^0\propto(1+\epsilon)K^0-(1-\epsilon)\bar{K}^0\,,$$
$$K_S^0\propto(1+\epsilon)K^0+(1-\epsilon)\bar{K}^0\,,\qquad(1)$$

where ϵ is the complex parameter describing the amount of CP violation.

Because the magnitude of ϵ is small ($\approx2.3\times10^{-3}$), K_L^0 decays primarily into CP-odd states and K_S^0 into CP-even states. In addition, CP violation may also be present in the decay amplitudes of K_S and K_L. Such, so-called, "direct" CP violation is characterized for the two-pion decay by the complex parameter ϵ' and is predicted to occur within the standard model due to second order weak transitions. However, the two most recent experimental searches for such an effect have not unambiguously established the presence of direct CP violation [3,4].

To search for evidence of direct CP violation in neutral kaon decay, Fermilab experiment 731 collected data on both K_L^0 and K_S^0 decaying simultaneously into the experimental apparatus. Two K_L^0 beams entered the active decay volume, whereupon one encountered a regenerator made of B_4C. The regenerator consisted of four blocks of this material, totaling two interaction lengths, with a scintillator following each block to veto decays and interactions occurring inside the regenerator. The regenerator alternated between the two K_L^0 beams during the course of data taking to reduce systematic errors. (A more detailed description of the apparatus may be found elsewhere [3,5,6].) Because K^0 and $\bar{K}^0$ interact differently in matter, K_S^0 were regenerated from the K_L^0 beam. Downstream of the regenerator, the number of decays into a final state can be described as a function of proper time τ as

$$\frac{dN}{d\tau}\propto F(E_K)e^{-X}[|\rho|^2e^{-\Gamma_S\tau}+|\eta|^2e^{-\Gamma_L\tau}+2|\rho|\,|\eta|\cos(\Delta m\tau+\phi_\rho-\phi_\eta)e^{-(\Gamma_S+\Gamma_L)\tau/2}]\,,\qquad(2)$$

where Γ_L and Γ_S are the decay widths of the K_L^0 and K_S^0, respectively, and Δm is their mass difference. The function $F(E_K)$ takes into account the energy spectrum of the incident beam and the factor e^{-X} accounts for absorption in the regenerator. Both of these factors can be accurately determined from the 2π decay modes. The parameter ρ is the regeneration amplitude and has a power law dependence on the kaon momentum, p_K: $\rho \propto g p_K^{-\alpha}$, where g is a geometric factor depending on the length and density of the regenerator [7]. From an extensive analysis of the 2π decay modes, it has been determined that $\alpha = 0.602 \pm 0.010$ for our regenerator (where the error is statistical only) [6]. The phase of the regeneration parameter, ϕ_ρ, is determined once α is known [8].

The complex parameter η in Eq. (2) parametrizes the level of CP violation for the given decay mode and is determined experimentally by measuring the ratio between the amplitudes for K_L and K_S decaying into a final state. In the absence of direct CP violation η is equivalent to ϵ. Currently, the value of η has been determined only for the $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes [9], with $|\eta_{+-}| = (2.268 \pm 0.023) \times 10^{-3}$ and $|\eta_{00}| = (2.253 \pm 0.024) \times 10^{-3}$. The phase angles for these complex parameters are $\phi_{+-} = 46.6 \pm 1.2$ and $\phi_{00} = 46.6 \pm 2.0$. The analogous CP-violation parameters for the decay into the final state $\pi^+\pi^-\gamma$ are here termed $\eta_{+-\gamma}$ and $\phi_{+-\gamma}$.

We have shown [10] how we isolated the $\pi^+\pi^-\gamma$ signal in our data and measured branching ratios for both K_S and K_L decays. As discussed in this reference, the decay of neutral kaons into $\pi^+\pi^-\gamma$ can occur through an inner-bremsstrahlung process, or IB, for both K_L^0 and K_S^0, where the photon is emitted by one of the final state pions through an $E1$ transition. This bremsstrahlung process does not affect the $\pi^+\pi^-$ decay vertex, therefore the CP characteristics are unchanged, namely, CP conserving for the K_S and CP violating for the K_L. Another type of decay can also occur, the direct emission, or DE, where the photon arises directly from the decay vertex, through an $M1$ transition. This type of decay is CP conserving for the K_L^0 and CP violating for the K_S^0 [11-13]. Because the $\pi^+\pi^-\gamma$ final state has these different contributions, $\eta_{+-\gamma}$ must be defined for a pure final CP eigenstate, specifically

$$\eta_{+-\gamma} = \frac{A(K_L \to \pi^+\pi^-\gamma, E1)}{A(K_S \to \pi^+\pi^-\gamma, E1)} . \tag{3}$$

If no mixing occurs between the DE and IB forms of decay, then the DE decay will modify Eq. (2) only by adding a term $[f/(1-f)]/|\eta|^2 e^{-\Gamma_L \tau}$ where f is the fraction of K_L^0 decays that occur through the DE process. If, however, the DE process can occur through an $E1$ transition, then mixing can occur between the two forms of decay and then the interference term of Eq. (2) will also be affected, forcing the fit value of $\eta_{+-\gamma}$ as defined in Eq. (3) to differ from η_{+-}. This would indicate that direct CP violation exists in this decay mode, with $\epsilon'_{+-\gamma} \neq 0$.

The preceding Letter describes the method of data selection for the $\pi^+\pi^-\gamma$ candidates, which resulted in 3841 events in the regenerator beam before background subtraction. (An estimate of 25 events as background was obtained from the sidebands in the reconstructed P_T^2 and mass spectra.) These events had photon energies in the kaon center of mass larger than 20 MeV. This sample includes a K_L DE component that decays downstream of the regenerator position. Because the K_S^0 decays are essentially purely IB, the photon energy spectrum of their decays can be used to separate IB from the DE component of K_L^0 decays. The fraction of K_L events with $E_\gamma^* > 20$ MeV which occur through the DE type of decay was determined to be $f = 0.685 \pm 0.041$.

Figure 1(a) shows the proper time distribution from the regenerator of all decays. Superimposed on this figure is the same distribution for Monte Carlo simulated $\pi^+\pi^-\gamma$ decays in our apparatus, normalized to the same number of events. The value for $\eta_{+-\gamma}$ in the simulation was taken to be the same as η_{+-}. Shown in Fig. 1(b) is the same plot, except that in this instance the Monte Carlo events were generated with no interference term between K_L^0 and K_S^0 decays. As this figure shows, the data require the existence of such an interference term, demonstrating that the CP characteristics of this decay are similar to the two-pion decay.

To fit the data for a quantitative result for the CP-violation parameters of the $\pi^+\pi^-\gamma$ decay, Eq. (2) (with the DE addition) was rewritten in terms of the kaon energy, E_K, and decay position in the laboratory, $Z_{\rm vtx}$, instead of the combined variable of proper time.

The data were histogrammed in the variables E_K (in bins of 10 GeV from 30 to 150 GeV) and $Z_{\rm vtx}$ (in bins of 2 m starting at the downstream face of the regenerator and extending 14 m downstream). An estimate for the distribution of background was made by binning, in the same way, the data which occurred in the mass sidebands, as discussed in Ref. [10]. This background estimate was then subtracted from the data sample. Bins with less than 8 events in them were not used in the fit,

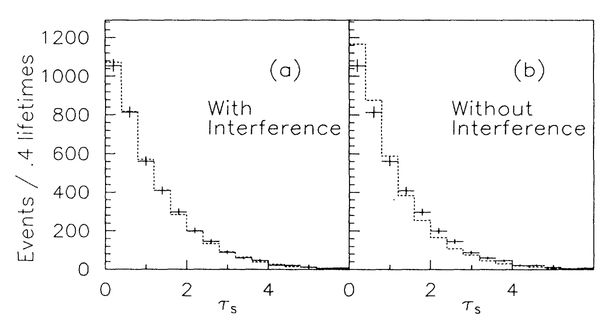

FIG. 1. The proper time distribution of $\pi^+\pi^-\gamma$ decays with respect to the regenerator. Panel (a) includes a comparison with Monte Carlo events containing an interference term between K_S and K_L while in (b) comparison is with simulated events having no such interference term.

leaving 53 data bins and 3671 events, after background subtraction. The data were then corrected, bin by bin, for the acceptance of our apparatus, as determined by Monte Carlo simulated events. The simulation contained more than 8 times the statistics of the data. The Monte Carlo simulation assumes an amplitude for DE decay containing a ρ propagator term as postulated by Lin and Valencia [11] and indicated by our results [10].

Free parameters in the fit were $\eta_{+-\gamma}$, $\phi_{+-\gamma}$, and an overall normalization. The currently accepted values for the lifetimes τ_S and τ_L of the K_S and K_L, and for their mass difference, Δm, were used [9] and were not allowed to vary. The value of α quoted above was used. No direct CP violation arising from the DE decay was allowed in the fit, so that if such an effect exists, it would modify the value of $\eta_{+-\gamma}$.

The result of the fit was

$$|\eta_{+-\gamma}| = (2.15 \pm 0.26) \times 10^{-3}, \quad \phi_{+-\gamma} = (72 \pm 23)^\circ . \tag{4}$$

The error is from the statistical uncertainty of the fit as determined by the fitting program. The χ^2 of the fit was 46 for 50 degrees of freedom. If the momentum exponent α in the regeneration amplitude ρ was allowed to vary as part of the fit, we obtained 0.613 ± 0.039 for its value, which agrees well with the value obtained from the two-pion decays.

To derive the estimate for the systematic error, parameters used in the fit were allowed to vary within their experimentally determined range. No significant effect on the fit outcome was obtained when kaon lifetimes or their mass difference were varied. A change of 0.02×10^{-3} in the fit value for $\eta_{+-\gamma}$, and 3° in $\phi_{+-\gamma}$, was seen if the expected background level was not subtracted from the data. An uncertainty of 0.005 m in the position of the regenerator (a conservative estimate obtained from the $\pi^+\pi^-$ data) translated to a change in the fit values of $\eta_{+-\gamma}$ and $\phi_{+-\gamma}$ of 0.02×10^{-3} and 1.5°, respectively. If the fixed value of α was allowed to vary by 0.01, then the fit results varied by 0.05×10^{-3} and 5°. Varying the value of f, the fraction of DE in K_L decays, resulted in a shift of 0.06×10^{-3} and 2° in the fit. Finally, we varied the acceptance correction linearly in $Z_{\rm vtx}$ or E_K, at a level statistically allowed by the $\pi^+\pi^-\gamma$ data. This level was 0.23% per meter for the $Z_{\rm vtx}$ acceptance, and 0.09% per GeV for the E_K acceptance. This is a conservative estimate for the systematic error arising from the acceptance correction, because the $\pi^+\pi^-$ and $\pi^0\pi^0$ data show no such level of disagreement with the Monte Carlo events. The change in the fit values of $\eta_{+-\gamma}$ and $\phi_{+-\gamma}$ resulting from the modification to the acceptance correction in $Z_{\rm vtx}$ was 0.10×10^{-3} and 3°, and from the modification to the E_K acceptance correction was 0.15×10^{-3} and 16°. All of the individual contributions to the total systematic error are shown in Table I. The total systematic error is 0.20×10^{-3} on the fit value for $\eta_{+-\gamma}$ and 17° on the fit value for $\phi_{+-\gamma}$.

The value of η obtained implies that the level of direct CP violation in this decay is small. If all of the difference between the fit value of $\eta_{+-\gamma}$ and the known value of ϵ were to be attributed to a direct CP-violation effect in the DE decay,

$$\eta_{+-\gamma} = \eta_{+-} - \epsilon'_{+-\gamma}, \tag{5}$$

and if the phase angles of these parameters are assumed to be equal, then a limit of

$$|\epsilon'_{+-\gamma}|/\epsilon < 0.3 \tag{6}$$

can be placed at the 90% confidence level.

To conclude, we have demonstrated that interference between K_L^0 and K_S^0 exists in the decay to the final state $\pi^+\pi^-\gamma$ and that the CP-violation parameters of this decay are consistent with those of the $\pi^+\pi^-$ and $\pi^0\pi^0$ decays. This result gives a limit on the level of direct CP violation in this decay.

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TABLE I. Systematic errors in the fit for $\eta_{+-\gamma}$ and $\phi_{+-\gamma}$.

Effect	Amount changed	Error on $\eta_{+-\gamma}$	Error on $\phi_{+-\gamma}$
Background subtraction	100%	0.02×10^{-3}	2°
Position of regenerator	0.005 m	0.02×10^{-3}	1.5°
Value for α	0.010	0.05×10^{-3}	5°
f (DE fraction)	0.041	0.06×10^{-3}	2°
$Z_{\rm vtx}$ acceptance	0.2% per m	0.10×10^{-3}	3°
E_K acceptance	0.09% per GeV	0.15×10^{-3}	16°
Total		0.20×10^{-3}	17°

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