Measurement of the Phase of the CP-Nonconservation Parameter η_{+-} and the K_S Total Decay Rate*

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The interference of K_S and K_L in the decay $K_{S,L} \to \pi^+\pi^-$ has been studied by use of the K_S regeneration technique. With utilization of the results for the regeneration phase presented in the preceding Letter, the phase of η_{+-} has been determined as a function of the K_L-K_S mass difference: $\varphi_{+-} = (45.5° \pm 2.8°) + 120°(\Delta m - 0.5348)/\Delta m$. The data also provide an accurate measurement of the K_S total decay rate: $\Gamma_S = [(1.122 \pm 0.004) + 0.16(\Delta m - 0.5348)/\Delta m] \times 10^{10}\ \mathrm{sec}^{-1}$.

Although a large number of models have been proposed to account for CP nonconservation, few, if any, place usefully stringent bounds on the magnitude of the effect. Consequently, considerable effort[1-3] has been placed on the measurement of the phase φ_{+-} [see Eq. (1), preceding Letter], for which a quite specific prediction

$$\varphi_{+-} = \tan^{-1}[2\Delta m/(\Gamma_S - \Gamma_L)] = 44.0° \pm 0.3° \qquad (1)$$

can be obtained from the "superweak" class of models[4] if the assumptions of unitarity and CPT invariance are made. Another class of models[5] allows deviations from this value up to a level limited by the violation of the $\Delta I = \frac{1}{2}$ rule in $K^0 \to 2\pi$ decay. As this violation is known to be small, an incisive test is obtained only if the experimental accuracy is at least of the order of $\pm 2°$.

The experiment consists of concurrently performed measurements of $\varphi_{+-} - \varphi_\rho$ from the $K \to \pi^+\pi^-$ data and φ_ρ from the charge asymmetry in the $K \to \pi^\pm l^\mp \nu$ decays. A major benefit of this approach is that the sensitivity of the φ_{+-} result to certain systematic effects is substantially reduced. The apparatus, event characterization, and the determination of φ_ρ have been discussed in the preceding Letter.

The observed $\pi^+\pi^-$ intensity in the forward direction following a regenerator placed in a pure K_L beam is given by

$$I(\tau, P_K) = \epsilon(\tau, P_K)S(P_K)\{|\rho|^2 \exp(-\Gamma_S\tau) + |\eta_{+-}|^2 \exp(-\Gamma_L\tau) + 2|\rho||\eta_{+-}|\exp[-(\Gamma_S+\Gamma_L)\tau/2]\cos(\Delta m\tau + \varphi_\rho - \varphi_{+-})\}. \qquad (2)$$

Here τ is proper time referred to the exit face of the regenerator, P_K the K^0 momentum, $\epsilon(\tau, P_K)$ the apparatus detection efficiency, $S(P_K)$ the momentum spectrum, and ρ the coherent regeneration amplitude.

The function $\epsilon(\tau, P_K)$ was evaluated by use of the Monte Carlo technique. The simulation was able to reproduce all relevant distributions of the experimental data with the required accuracy. The detection efficiency for the interval $5 < P_K < 6$ GeV/c is shown in Fig. 1, curve a.

An event was accepted as $K \to \pi^+\pi^-$ if the following conditions were satisfied: (1) no Cherenkov or muon counter signals; (2) $M_{\pi\pi} = M_K \pm 2\sigma$, where σ is the K^0 momentum-dependent mass resolution, typically about 2.5 MeV/c^2; (3) $4 \leq P_K < 10$ GeV/c; (4) $1.4 < P_\pi < 7$ GeV/c; (5) $\chi^2 < 16$ (see preceding paper for definition of χ^2); (6) various decay-volume, spectrometer, and counter-boundary fiducial cuts designed to ensure clean registration of the $\pi^+\pi^-$ decay; and (7) inbending trajectories. Approximately 2×10^6 events survived these cuts. The distribution of the invariant mass is given in Fig. 2; with no free parameters in the reconstruction, the K^0 mass is found to be 498.15 MeV/c, close to the current average value[6] of 497.87 ± 0.32 MeV/c^2.

As was done in the analysis of the semileptonic decays, the data have been again analyzed in P_K intervals of 1 GeV/c to allow for momentum variation of the regeneration amplitude and phase.

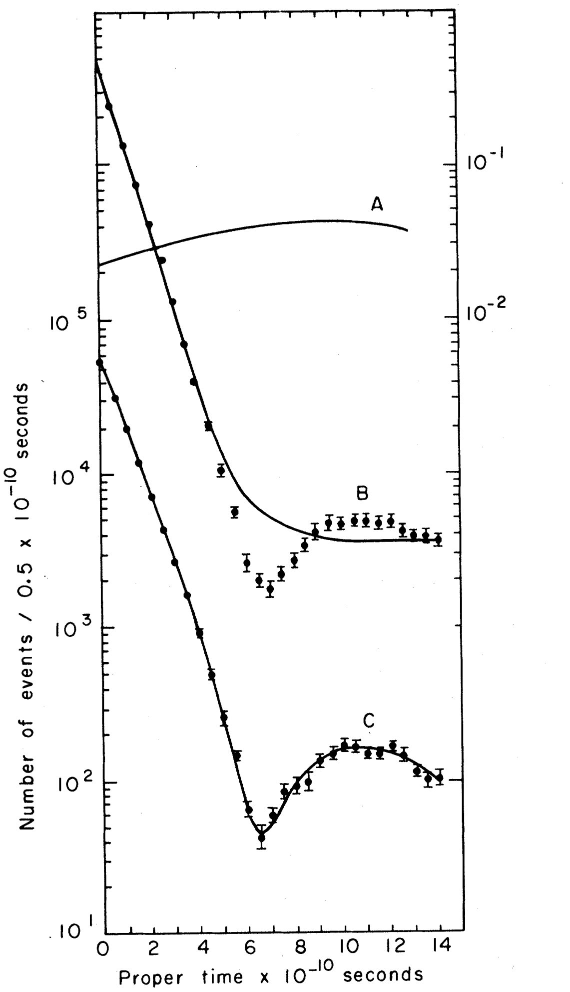

FIG. 1. Curve *a*: The Monte Carlo–derived efficiency for the momentum interval $5<P_K<6$ GeV/*c*. The absolute value is given by the right-hand ordinate. Curve *b*: Efficiency-corrected data summed over P_K. The smooth curve is the intensity if K_S^0-K_L^0 interference is neglected. Curve *c*: Data for the interval $5<P_K<6$ GeV/*c*, uncorrected for the detection efficiency. The smooth curve is the fit of Eq. (5) to the data.

The separation of the coherent and incoherent events was accomplished by a subtraction in $P_\perp^2$ for each proper time and momentum bin. In addition to the removal of the diffractively and/or inelastically scattered contribution, a very small residual background of $K_{\mu 3}$ decays was also eliminated by a subtraction in the invariant-mass distribution.

Data for a representative momentum interval, $5<P_K<6$ GeV/*c*, are shown in Fig. 1, curve *c*. The existence of destructive interference around $\tau=7\times10^{-10}$ sec is a prominent feature of the data

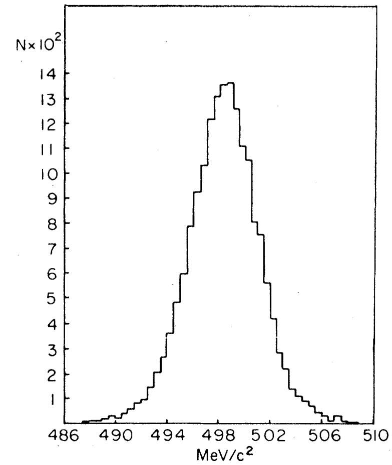

FIG. 2. Invariant-mass distribution for the $K_{S,L}^0 \to \pi^+\pi^-$ mode.

at all momenta. The efficiency-corrected data summed over all momenta are shown in Fig. 1, curve *b*, along with the intensity which would be expected in the absence of K_S-K_L interference.

By use of the optimization program MINUIT, the data for each momentum interval have been fitted simultaneously by Eq. (2) for $S(P_K)$, $|\rho/\eta_{+-}|$, $\varphi_{+-}-\varphi_\rho$, and an overall, momentum-independent Γ_S, with $\Delta m/\hbar$ and Γ_L fixed at values of 0.54×10^{10}/

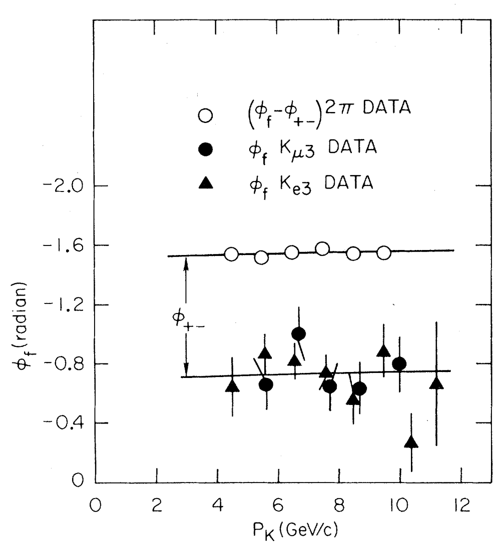

FIG. 3. Results of the combined fit for φ_{+-}. The data points for φ_f are from Table I of the preceding Letter; the $\varphi_{+-}-\varphi_f$ data are from Table I. The fitting procedure yields two parallel straight lines describing the 2π and K_{l3} data, and whose difference at any momentum is φ_{+-}. The momentum dependence of φ_f is determined almost entirely by the 2π data.

sec and 1.93×10^7/sec, respectively.[6] The total χ^2 for the fits is 103.7 for 127 degrees of freedom. The data and the fit for the interval $5 < P_K < 6$ GeV/c are shown in Fig. 1, curve c. The phase results for each momentum interval are given in Table I.

The results for $|\rho/\eta_{+-}|$ are of interest in themselves, and will be the subject of a future publication. The overall result for Γ_S is

$$\Gamma_S = [(1.124\pm0.004)+0.16(\Delta m-0.540)/\Delta m]\times10^{10}\ \text{sec}^{-1}, \tag{3}$$

in good agreement with recently reported results[3,7] but not with some earlier results.[8] The quoted error includes estimates of the possible systematic errors in the Monte Carlo–derived efficiency, magnetic field map, and event reconstruction.

The dependence of the results for $\varphi_{+-}-\varphi_f$ on Δm is found to be

$$\varphi_{+-}-\varphi_f = (\varphi_{+-}-\varphi_f)_m + 184°\left(\frac{\Delta m-0.540}{\Delta m}\right), \tag{4}$$

where the subscript m refers to values measured in this experiment. In the extraction of φ_{+-}, however, this strong correlation is partially offset by a similar correlation of the φ_f results which enter in the opposite sense. With use of the φ_f results given in Table I of the preceding Letter and the results for $\varphi_{+-}-\varphi_f$ in Table I, a fit was made for φ_{+-}, shown in Fig. 3. The result is

$$\varphi_{+-} = (46.7°\pm120°)\times(\Delta m-0.540)/\Delta m. \tag{5}$$

The considerable disagreement of the recently reported values for Γ_S,[3,7] and $|\eta_{+-}|$,[3,9] with previous results affects most of the reported values for Δm in a non-negligible way. Because of apparent discrepancies and in some instances the absence of stated sensitivities, reliable corrections cannot be made at present for most of the older values. However, the result of Cullen *et al.*[10] and a new very precise Δm value by Geweniger *et al.*[11] can be employed safely to give an average value of $\Delta m = 0.5348\pm0.0021$. This value of Δm for the present work leads to

$$\Gamma_S = (1.122\pm0.004)\times10^{10}\ \text{sec}^{-1},\quad \varphi_{+-} = 45.5°\pm2.8°, \tag{6}$$

TABLE I. Results for $\varphi_{+-}-\varphi_f$ versus P_K.

P_K interval (GeV/c)	$\varphi_{+-}-\varphi_f$ (rad)
4–5	1.537 ± 0.027
5–6	1.511 ± 0.025
6–7	1.547 ± 0.027
7–8	1.576 ± 0.031
8–9	1.544 ± 0.042
9–10	1.545 ± 0.065

in good agreement with the prediction [Eq. (1)] of the superweak model. As the possible impact of the other Δm measurements on the present result [Eq. (6)] is not expected to exceed 0.5°, the compatibility of the present result with the superweak model is secure. Good agreement is also obtained with the value $\varphi_{+-} = 46.4°\pm1.60°$ obtained by study of K_S-K_L interference in a short neutral beam.[12]

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