DETERMINATION OF THE PHASE OF THE CP-NONCONSERVATION PARAMETER η_{+-} IN NEUTRAL K DECAY*

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This Letter reports upon a determination of the phase of the parameter η_{+-} defined as

$$\eta_{+-}=\frac{\langle\pi^+\pi^-|K_L{}^0\rangle}{\langle\pi^+\pi^-|K_S{}^0\rangle},\qquad(1)$$

where the numerator and denominator are the amplitudes for $K_L{}^0$ and $K_S{}^0$ decay into $\pi^++\pi^-$, respectively. The phase of η_{+-} was determined by measuring the phase between $K_L{}^0\rightarrow\pi^++\pi^-$ and regenerated $K_S{}^0\rightarrow\pi^++\pi^-$ and by evaluating the regeneration phase by means of an optical-model calculation.

The magnitude of η_{+-} was measured in experiments which established the existence of the decay $K_L{}^0\rightarrow\pi^++\pi^-$.[1-4] Later experiments, including this one, verified the existence of the above reaction, by observing the interference between $K_L{}^0$ and $K_S{}^0$ decay amplitudes.[5-8]

The experiment consists in having a $K_L{}^0$ beam pass through various thicknesses of copper regenerators and looking at the time dependence of forward-going neutral K decays into $\pi^++\pi^-$ downstream from the regenerators. Since the emerging beam is a coherent mixture of $K_S{}^0$ and $K_L{}^0$ mesons, the amplitudes for decay into $\pi^+\pi^-$ combine to give a decay distribution in time which is the sum of two exponentials with an added interference term.

The experiment was performed in the 30° neutral beam of the Argonne zero-gradient synchrotron (ZGS). The observed beam momentum varied between 0.7 and 2.0 BeV/c and had a mean value of 1.1 BeV/c. Useful decays, occurring in a 12-in. long vacuum pipe at 60 ft from the target, were momentum analyzed with 1-mil Al-foil spark chambers placed in a 9.8-kG magnetic field. (The equipment is described by Verhey et al.[9]) Data were taken for 0-, $\frac{1}{2}$-, $\frac{3}{2}$-, and 3-in. copper regenerators. The film was digitized, after scanning, on CHLOE,[10] the Argonne Laboratory's computer-controlled flying-spot scanner, and then processed by pattern recognition programs on an IBM 7094.

For each event the invariant mass was computed assuming decay into two pions. Figure 1(a) shows the histograms for the data obtained. For the 3-in. data the peak is at 498.7 MeV and the full width at half maximum is 16 MeV. In Fig. 1(b) the angular distribution for those events with an invariant mass between 475 and 515 MeV is plotted. The variable θ is the angle between the beam direction and the vector sum of the momenta of the two decay particles. The forward peak contains primarily 2π decays of transmitted K's while the background consists of diffraction-regenerated K decays and a few leptonic decays. The rms width of the forward peak is 6 mrad and is caused by the resolution of the equipment and the angular divergence of the beam.

To obtain the time distribution of coherent 2π events, the data with an invariant mass between 485 and 515 MeV were divided into proper-time bins with the zero in time taken as the downstream end of the anticoincidence counter which followed the regenerator. Coherent events were chosen as those with $\frac{1}{2}\theta^2\times10^5<9$. A background subtraction was made by extrapolation to the forward interval of the events in the angular region $30\leq\frac{1}{2}\theta^2\times10^5<60$.

The proper time distribution of 2π events for each thickness was fitted to equations of the form

$$F_i(t)=M_iE(t)[R_i{}^2e^{-\Gamma_St}+1+2R_ie^{-\Gamma_St/2}\cos(\delta\Gamma_St+\varphi)],\qquad(2)$$

where M_1 is the normalization constant proportional to the exposure at each thickness. It was computed from the beam-monitor counts corrected for nuclear absorption in the absorber and also from the number of observed leptonic decays of $K_L{}^0$ mesons corrected for decays of elastically scattered events. $E(t)$ is the efficiency for 2π decays as a function of proper time calculated by Monte Carlo techniques. R_1 is the ratio of regeneration amplitude A to CP-nonconserving amplitude η_{+-}, where

$$A=\frac{if_{21}(0)N\lambda\Lambda}{i\delta+\frac{1}{2}}(1-e^{-l/2-i\delta l}).\qquad(3)$$

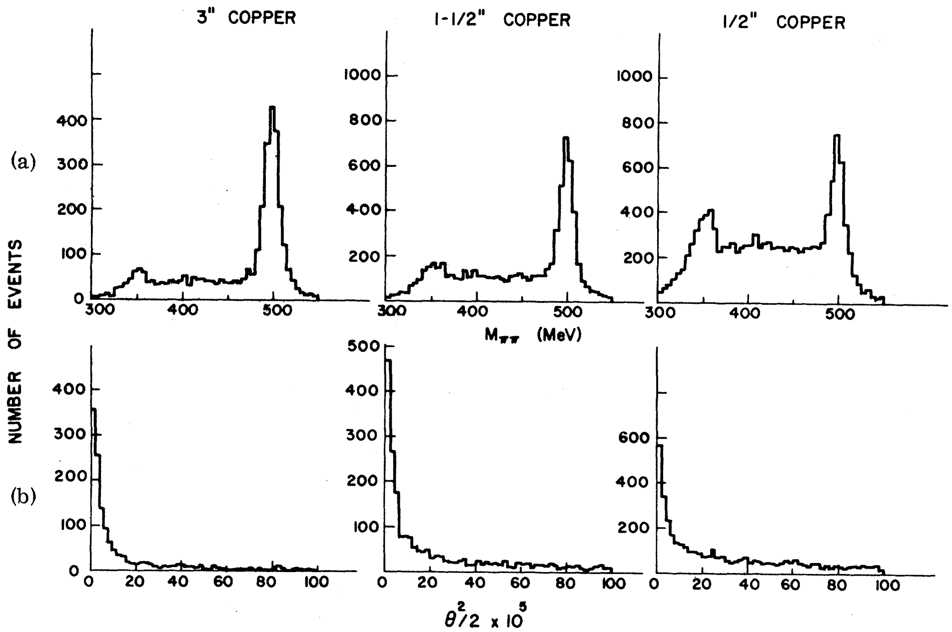


FIG. 1. (a) Invariant mass plot of all data assuming $K^0 \rightarrow \pi^+ + \pi^-$. (b) Angle of reconstructed particle relative to beam direction for $485 \leq M_{\pi\pi} \leq 515$ MeV.

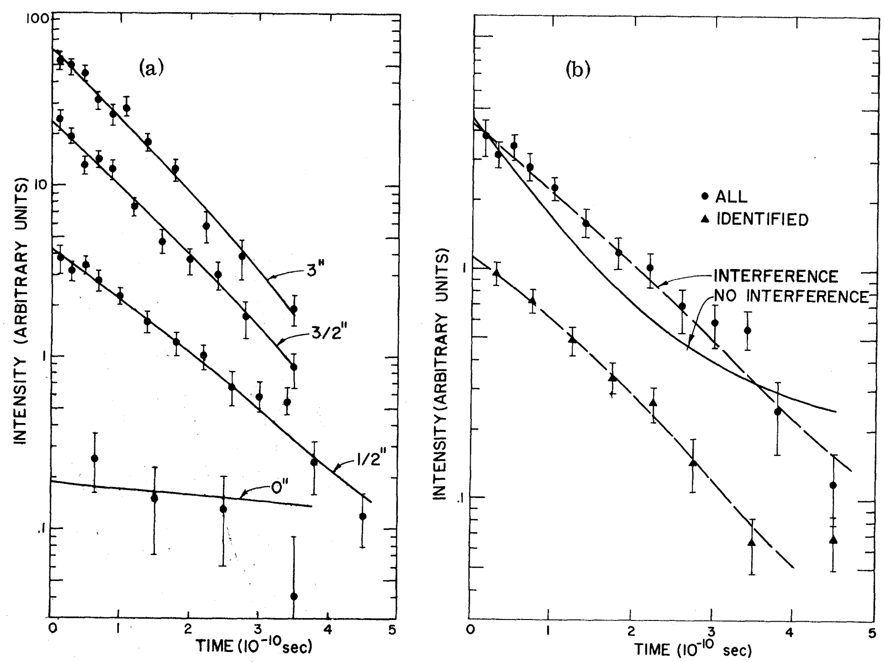


FIG. 2. (a) Time distribution for 0-, $\frac{1}{2}$-, $1\frac{1}{2}$-, and 3-in. copper regenerator. (b) Time distribution for $\frac{1}{2}$-in. copper regenerator. Dashed curve is fit assuming interference; solid curve is fit assuming no interference. Lower data points are those where both particles were identified as pions.

N is the number of nuclei/cm^3, λ is the incident-beam wavelength, and Λ is the mean decay length of the K_S^0. l is the thickness of regenerator in units of Λ, $f_{21}(0)$ is the forward regeneration amplitude for K_S^0 mesons from K_L^0 mesons, $\Gamma_S = 1.136 \times 10^{10}$ sec^{-1} is the decay rate of K_S^0, $\delta = (m_S - m_L)/\Gamma_S$ is the mass difference between K_S^0 and K_L^0, and $\varphi = \arg\eta_{+-} - \arg A$. Figure 2(a) shows the best fit to all four thicknesses with single values for the parameters φ, δ, and $|f_{21}(0)|$. Figure 2(b) shows the fits for the $\frac{1}{2}$-in. regenerator alone with and without the assumption of interference and the fit with interference to those events where both particles were identified as π mesons in the range chambers. The results of the fitting give

$$\delta = \pm 0.57 \pm 0.10;$$

$$\varphi = \mp 1.10 \pm 0.34,$$

where $\mp$ refers to the sign of the mass difference;

$$|f_{21}(0)| = 9.7 \pm 0.8 \text{ F}.$$

The magnitude of η_{+-} has been assumed to be 1.96×10^{-3}.

The measured φ may be related to $\arg\eta_{+-}$ by evaluating the argument of Eq. (3). The second term has been calculated for our mean momentum and $\frac{1}{2}$-in. Cu to be ∓ 0.07 rad. An optical-model calculation[11] has been performed to obtain $\arg[if_{21}(0)]$ from K-nucleus interaction potentials. Since K-Cu scattering amplitudes have not been measured, the K-nucleus interaction potentials were found from charged K-nucleon scattering amplitudes.

The imaginary parts of the scattering amplitudes were found (using the optical theorem) from total cross sections taken from the summary in Barashenkov and Maltsev[12] for K^+n and K^-n and from Cool et al.[13] for K^+p and K^-p. The real K^+p potential has been measured by Zorn and Zorn[14] at 568 and 656 MeV/c and by Cook et al.[15] at 970, 1170, and 1970 MeV/c. The data of Holley[16] were used for the real K^-p scattering amplitude. For the nuclear density, a trapezoidal distribution of the form

$$\rho(r) = \rho_0, \quad 0 \leq r < r_0,$$

$$\rho(r) = \rho_0\left(\frac{R-r}{R-r_0}\right), \quad r_0 \leq r \leq R, \tag{4}$$

was used. For copper the values $r_0 = 2.7$ F and $R = 5.7$ F were assumed.

The resultant K-Cu potentials are shown in Fig. 3(a). The imaginary parts are negative, but the signs of the real parts are uncertain. Since the data of Zorn and Zorn[14] indicate the K^+-p system is repulsive, ReV is taken positive, but both signs of Re$\bar{V}$ are considered. The resultant $f_{21}(0)$ are shown in Fig. 3(b) as a function of the momentum of the K and the sign of Re$\bar{V}$. The magnitude of $f_{21}(0)$ is seen to vary between about 7 and 12 F and to have a mean value of about 9.5 F integrated over our K_L^0 spectrum. The mean calculated value for the magnitude of $f_{21}(0)$ agrees well with 9.7 ± 0.8 found by fitting the data. The mean value for $\arg f_{21}(0)$ averaged over the K_L^0 spectrum is 220° if Re$\bar{V} < 0$ and 237° if Re$\bar{V} > 0$. Varying ReV or Re$\bar{V}$ by 20% changes the phase by 8°. The best estimate is

$$\arg[f_{21}(0)] = -2.30 \pm 0.28 \text{ rad},$$

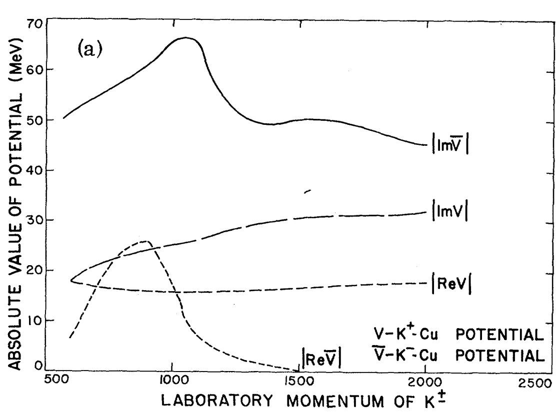
or

$$\arg[if_{21}(0)] = -0.73 \pm 0.28 \text{ rad}.$$

These results for $f_{21}(0)$ agree well with a calculation by Cabbibo,[17] who obtains

$$0.4 < -\arg[if_{21}(0)] < 0.8.$$

They also agree well with the measurements



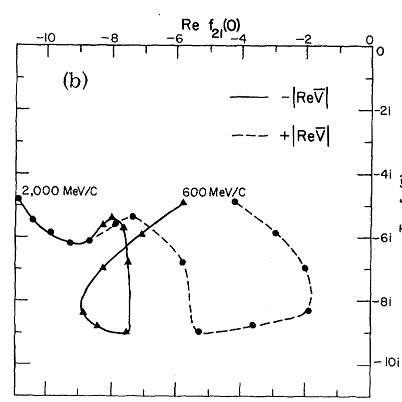


FIG. 3. (a) Optical-model potentials calculated from $K^\pm$-p and $K^\pm$-n scattering cross sections. (b) Regeneration amplitude $f_{21}(0)$ as a function of K_L^0 energy in 100 MeV/c intervals.

Table I. Summary of the determinations of $\arg\eta_{+-}$.

Experiment	φ	$\arg\eta_{+-}$	Reference
Bott-Bodenhausen et al.	$-1.54^{+0.37}_{-0.44}$		6
Alff-Steinberger et al.	-1.41 ± 0.18	$+0.60\pm0.23$	7
Firestone et al.	$\cdots$	$+0.52\pm0.79$	8
This experiment	-1.17 ± 0.34	$+0.44\pm0.44$	

in iron of $\arg f_{21}(0)$ at 760 MeV/c by Piccioni and his collaborators,[18] who obtain $\arg f_{21}(0) \approx 225°$, and reasonably well with an optical-model calculation by Rubbia and Steinberger,[7] using $K^{\pm}$-carbon scattering data of Cool et al.[7] to obtain $\arg f_{21}(0) = 223°$ in copper at a mean energy of 2.6 GeV/c.

Since the sign of δ has been determined to be negative,[18-21] we obtain

$$\arg\eta_{+-} = +0.44 \pm 0.44.$$

A summary of the determinations of $\arg\eta_{+-}$ is listed in Table I.

The results agree with most models of CP nonconservation which predict $\arg\eta_{+-} \approx \arctan(2\Delta m/\Gamma_S) \approx 45°$. The equality is exact for the superweak model of Wolfenstein.[22] Further analysis of the nature of CP nonconservation in neutral K decay depends largely on knowledge of the parameter η_{00} for decay into the $\pi^0\pi^0$ mode.

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STUDY OF THE $\pi\pi$ S-WAVE PHASE SHIFT IN THE ρ REGION TAKING INTO ACCOUNT ABSORPTION EFFECTS*

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This note contains a determination of the $\pi\pi$ $I=0$, S-wave phase shift in the ρ region under certain assumptions about the effects of absorption on the differential cross section for the reactions $\pi^- + p \rightarrow \pi^+ + \pi^- + n$. The model which we employ is discussed, and the results of applying the model to data from $\pi^- p$ interactions at 2.7 GeV/c are presented.

The data at 2.7 GeV/c show that the reactions

$$\pi^- + p \rightarrow \pi^+ + \pi^- + n, \qquad (1)$$

$$\pi^- + p \rightarrow \pi^0 + \pi^- + p, \qquad (2)$$

are dominated by ρ production.[1] When Reaction (2) was fitted to the absorption-modified one-pion-exchange model due to Gottfried and Jackson,[2] the theoretical cross section for ρ^- and ρ^0 and the density-matrix elements for ρ^- showed good agreement with our data at 2.7 GeV/c.[1] The Gottfried-Jackson model[2] does not include S-, P-wave interference effects, and thus cannot be applied to the study of the observed ρ^0-decay asymmetry.[1] Consequently, we have modified this absorption model to include an $I=0$, $J=0$ amplitude in the spirit of Gottfried and Jackson[2] and Durand and Chiu.[2,3]

Several authors have attributed this asymmetry to the interference of the $I=0, J=0$ and $I=1$, $J=1$ $\pi\pi$ elastic scattering amplitudes.[4] Durand and Chiu[3] have calculated the ρ^0 density-matrix elements including a $J=0, I=0$ resonance and find agreement with the experimental ρ^0-decay angular distribution averaged over the ρ^0 mass region. Hagopian and Selove[5] see evidence for an $I=0, J=0$ resonance in the $\pi^+\pi^-$ effective-mass spectrum. On the other hand, analyses by Jacobs[6] and Jabiol, James, and Nguyen[7] are in disagreement with Hagopian and Selove. A theoretical calculation by Finkelstein[8] shows a decreasing S-wave phase shift in accordance with a suggestion by Chew.[9] Dilley[10] has pointed out the possibility that a slowly increasing S-wave phase shift may go through 90° without being resonant. Estimates of the S-wave $\pi\pi$ phase shift have been calculated from experimental data by Jones et al.,[11] Wolf,[12] and Baton and Reignier.[13] None of these determinations has included absorption effects. But it is known that absorption effects introduce an isotropic term into the ρ-decay distribution[1,2]; thus in calculating the S-wave $\pi\pi$ phase shift as a function of the $\pi\pi$ effective mass, we have introduced absorption corrections.

Our model for calculating the S-wave phase shifts assumes the following:

(a) The absorption model, modified to include an S-wave amplitude, describes correctly the θ^* dependence of the $\pi\pi$-decay angular distribution in the region $0.8 < \cos\theta^* < 1$, where θ^* denotes the angle between the incident π^- and the outgoing di-pion in the over-all center-of-mass system.

(b) The ρ^0-decay angular distribution at the limit of the experimentally accessible region ($\cos\theta^* = 1.0$) is the same as the on-mass-shell distribution at the pole $\Delta^2 = -\mu^2$, where Δ^2 denotes the square of the four-momentum transfer to the recoil neutron and μ denotes the pion mass.

(c) Only $I=0, J=0$ and $I=1, J=1$ partial waves are considered.

(d) The P-wave phase shift for on-the-mass-shell $\pi\pi$ scattering is given by

$$\tan\delta_1^{\,1} = \frac{\omega_r}{\omega_r^{\,2} - \omega^2} \frac{2(q/q_r)^3}{1+(q/q_r)^2} \Gamma_r, \qquad (3)$$