Measurement of the Phase and Magnitude of η_{00}

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This Letter presents measurements of the phase and magnitude of the CP-nonconservation parameter η_{00} resulting from a study of the proper-time distribution of $K^0 \to \pi^0\pi^0$ decays in a short-lived neutral beam. We find $\varphi_{00} = 55.7° \pm 5.8°$ and $|\eta_{00}| = (2.33 \pm 0.18) \times 10^{-3}$. A direct comparison to η_{+-} measured in the same experiment gives $\varphi_{00} - \varphi_{+-} = 12.6° \pm 6.2°$ and $|\eta_{00}/\eta_{+-}| = 1.00 \pm 0.09$.

We report the results of an experiment designed to measure the phase of the CP-nonconservation parameter $\eta_{00} = A(K_L^0 \to \pi^0\pi^0)/A(K_S^0 \to \pi^0\pi^0)$ by observing the proper-time distribution of $2\pi^0$ decays in a short-lived neutral-kaon beam. The experiment was performed at the Brookhaven National Laboratory alternating-gradient synchrotron.

The experimental arrangement is shown in Fig. 1. Kaons were produced by 28.5-GeV/c protons incident on a 3.5-in.-long platinum target. A neutral beam was defined at 70 mrad to the proton direction by a 72-in.-long brass collimator with an aperture of 7 mrad horizontally and 14 mrad vertically. The collimator was immersed in a magnetic field of 20 kG to sweep charged particles from the neutral beam and reduce the flux of muons passing through the apparatus. γ rays were absorbed from the beam by 2 in. of Hevimet placed at the entrance to the collimator, 20 in. downstream from the platinum target.

The spectrometer detected kaons that decayed in a 140-in. helium-filled region beginning 120 in. from the production target. At least two of the γ rays from the decay $K^0 \to 2\pi^0 \to 4\gamma$ were converted to pairs in three lead sheets (0.3 radiation lengths each). The directions of these γ rays

were determined from the tracks of the pairs through a system of ten proportional wire chambers. The energies and coordinates of all four γ rays were recorded by a two-plane lead-glass calorimeter. The aperture defined by the lead-glass array was surrounded by layers of lead and scintillator designed to veto events with extra γ rays from the decay $K_L^0 \to 3\pi^0 \to 6\gamma$, the major source of background in the experiment. The entire apparatus was mounted on rails and could be rolled along the neutral-beam direction. Charged particles were momentum analyzed in the same apparatus by energizing the 72D18 spectrometer magnet. The $K^0 \to \pi^+\pi^-$ decays obtained in this manner determine the phase and magnitude of η_{+-}, as described in the following Letter.[1]

A decay to neutral pions was signaled by the absence of a pulse in the four "N" scintillation counters at the entrance to the apparatus and in the γ-ray vetoes, one or two hits in the first two proportional wire chambers (PWC's) immediately following the first lead converter, two or more hits in each of the eight remaining PWC's, and at least 1.5 GeV of energy in each side of the lead-glass array. About 15 triggers/sec (for 2×10^{10} protons/sec) were recorded. A total of 16
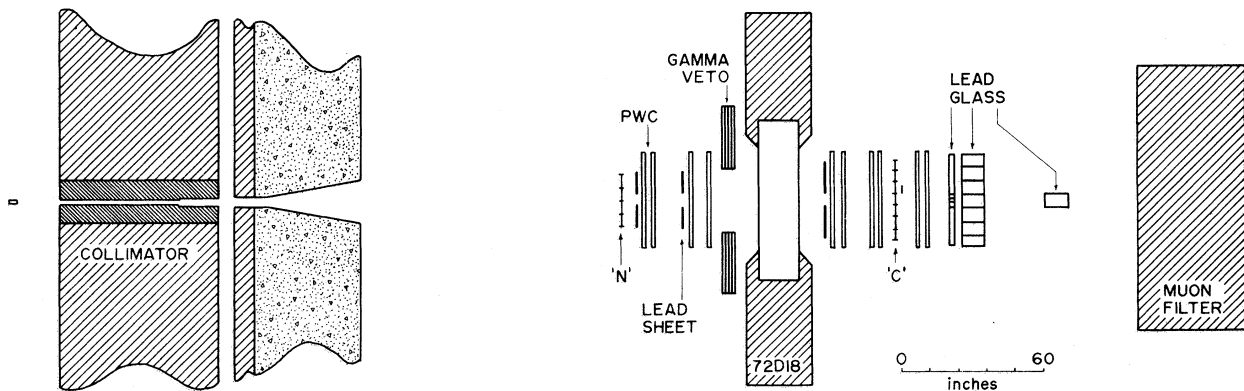

FIG. 1. Plan view of experimental layout.

million triggers were accumulated in two positions of the apparatus separated by 40 in. along the beam line.

The energy calibration of each lead-glass detector was determined *in situ* with use of momentum-analyzed electrons from K_{e3} decay. Seven calibrations were made during the data-taking period. Short-term drifts were removed with the aid of pulse-height spectra obtained frequently from ambient muons. The energy resolution of the system was found to be $\sigma_E/E = 0.02 + 0.04E^{-1/2}$. A study of energy sharing with adjacent blocks as a function of the position of incident electrons enabled us to locate γ-ray showers to 0.7 in. in the 6-in. blocks.

An event was reconstructed by first identifying distinct energy clusters in the lead-glass system. A total of 2.2 million candidates contained four clusters totaling at least 8 GeV in energy. By use of "roads" from possible conversion points to each of the energy clusters, two continuous tracks were found, thus determining the position of the decay vertex. The angular resolution for a converted γ ray was ~ 6 mrad, arising largely from multiple scattering in the lead sheets. The directions of unconverted γ rays were calculated from the vertex and energy centers of gravity.

The four γ rays were associated with two pions by computing the effective masses of the three possible sets of two γ-ray pairs. Of those events which had a good vertex within the decay region, 80% had a unique pairing that yielded masses between 90 and 180 MeV. A total of 190 000 events survived the reconstruction.

A fit was made to each event constraining the γ-pair mass to be that of the π^0, to extract improved values of the directions and momenta of the γ rays and the coordinates of the vertex. The reconstructed π^0-π^0 mass is shown in Fig. 2 for all of the data and for events with proper times between 8–9 K_S lifetimes, where the CP-nonconserving interference is maximal.

The length of flight (Z) and momentum (P) determine the proper time $\tau = M_K Z/P$ of each event. The resolutions (standard deviation) were 3% in P and 10 in. in Z. The resultant uncertainty in proper time is $0.4\tau_S$, more than adequate to delineate the features of the interference term which has a period of $13\tau_S$. An unbiased measure of the proper time requires that the absolute Z and P scales be correct, free of systematic shifts. A direct comparison of $2\pi^0$ decays following a lead regenerator placed in the beam, to Monte Carlo–simulated events, indicates that the true vertex
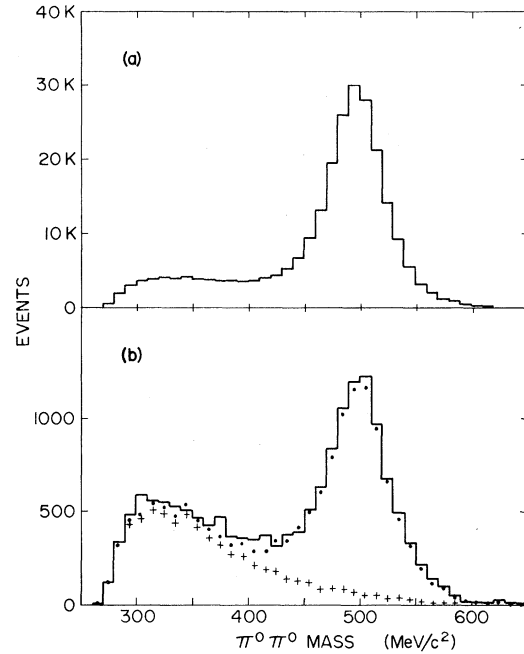

FIG. 2. Reconstructed π^0-π^0 mass. (a) All data; the rms width is 21 MeV/c^2. (b) Data with $8\tau_S < \tau < 9\tau_S$. Monte Carlo estimates of the $3\pi^0$ background (crosses) and of the sum of $2\pi^0$ and $3\pi^0$ (dots) are shown.

is known to 2 in. The momentum scale is known to 0.5% from the fact that the mean reconstructed $2\pi^0$ mass lies within 2 MeV/c^2 of the correct value. These two limits constrain the possible bias in the proper-time scale to $0.07\tau_S$.

The residual $3\pi^0$ background was removed from the data with the aid of a Monte Carlo simulation. The mass distribution of the data between 270 and 650 MeV/c^2 in each 1 GeV/c by 10 in. (P,Z) bin was fitted by the sum of Monte Carlo–generated $2\pi^0$ and $3\pi^0$ spectra. The true number of $2\pi^0$ decays in the mass region 400–600 MeV/c^2 was estimated by subtracting this background. An example of this fit is shown in Fig. 2(b).

After the data reduction and background removal, 85 000 events remain in a useful decay volume with momenta between 8 and 18 GeV/c: 44 000 with the apparatus in an upstream position and 41 000 with the apparatus rolled 40 in. downstream. Following correction for the detection efficiency of the apparatus, the data in each (P,Z) bin were normalized to the total number of events at that momentum to render the analysis independent of the momentum spectrum. These data are shown in Fig. 3(a), plotted as a function of proper time. The data were compared with the expected $2\pi^0$ in-
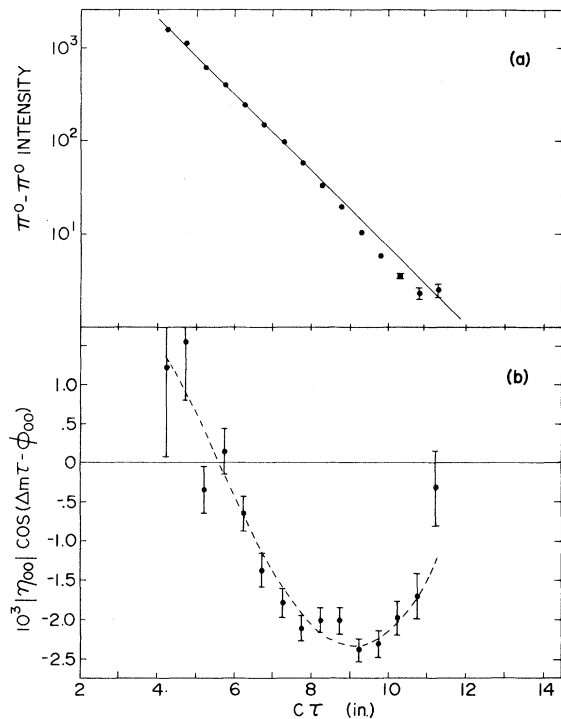
FIG. 3. (a) Efficiency-corrected data. The solid line represents the intensity in the absence of CP non-conservation. (b) CP-nonconserving interference extracted from the data. The smooth curve is $|\eta_{00}|$ $\times \cos(\Delta m \tau - \varphi_{00})$, with use of the best-fit parameters for φ_{00} and $|\eta_{00}|$.

FIG. 4. Dependence of χ^2, $|\eta_{00}|$, and φ_{00} on the K_S lifetime. The vertical band represents $\pm$ 1-standard-deviation limits from the K_S lifetime measured in previous experiments (Ref. 2).

tensity

$$I = \exp(-\tau/\tau_S) + |\eta_{00}|^2 + 2D(P)|\eta_{00}|$$

$$\times \cos(\Delta m \, \tau - \varphi_{00}) \exp(-\tau/2\tau_S). \quad (1)$$

The third term in this equation represents the CP-nonconserving interference between K_S and K_L decays and is proportional to the dilution factor $D(P)$ defined as the difference divided by the sum of the K^0 and $\overline{K}^0$ intensities at the production target. $D(P)$ is determined from our analysis of $K^0 \to \pi^+ \pi^-$ decays. The intensity in Eq. (1) is slightly distorted by coherent regeneration and diffraction scattering in the Hevimet γ filter and the walls of the beam-defining collimator. This correction is incorporated as a (P, Z)-dependent modification to Eq. (1). By use of a value[2] for the lifetime $c\tau_S$ = 1.053 ± 0.003 in. and a K_L-K_S mass difference $(\Delta m)\tau_S$ = 0.4774 ± 0.0020,[2] a two-parameter fit to the data gives φ_{00} = 55.7° ± 5.4° and $|\eta_{00}|$ = (2.33 ± 0.18) × 10^{-3}, with χ^2 = 157 for 171 degrees of freedom. Parameters determined from the data in the two positions of the apparatus are statisti-
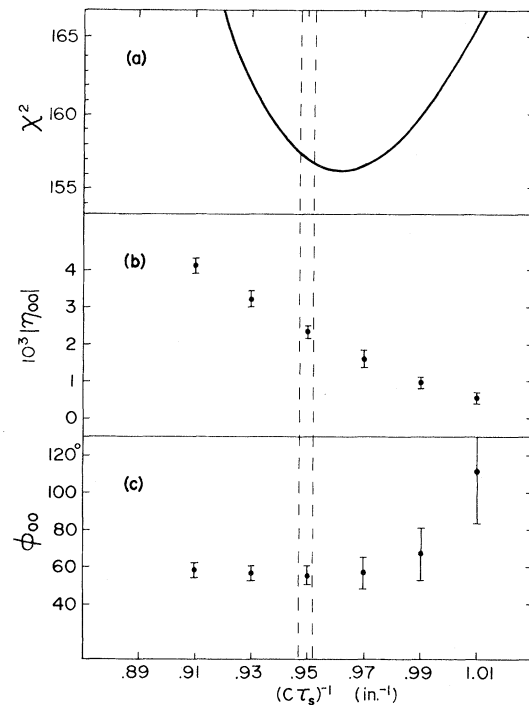
cally consistent. Figure 3(b) shows the data representing the interference term, with the exponential decay factor removed.

The dependence of χ^2, $|\eta_{00}|$, and φ_{00} on the lifetime τ_S is shown in Fig. 4. The value favored by this experiment, $c\tau_S$ = 1.037 ± 0.014 in., agrees with recent measurements.[2]

Systematic errors in φ_{00} are estimated to be 2° from uncertainty in the proper-time scale and 0.7° from regeneration and diffraction in the filter and collimator. The quoted uncertainty in the mass difference Δm contributes 0.9°. Including these small errors, we obtain a final result of φ_{00} = 55.7° ± 5.8°. The error in $|\eta_{00}|$ is unaffected. Three measurements of φ_{00} prior to this experiment gave φ_{00} = 51° ± 30°,[3] φ_{00} = 38° ± 25°,[4] and φ_{00} - φ_{+-} = 7.6° ± 18°.[5]

This single experiment provides a direct comparison of the phase and magnitude of η_{00} and η_{+-} under the same conditions, free of most systematic errors. The phase difference φ_{00} - φ_{+-} is unaffected by Z or P shifts common to the two measurements and by uncertainties in the mass difference and in the estimate of coherent regeneration in the filter and collimator. The ratio of

magnitudes $|\eta_{00}/\eta_{+-}|$ is largely independent of the dilution factor. We find $\varphi_{00} - \varphi_{+-} = 12.6° \pm 6.2°$ and $|\eta_{00}/\eta_{+-}| = 1.00 \pm 0.09$.[6]

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[6]Two previous measurements of $|\eta_{00}/\eta_{+-}|$ have been published: 1.03 ± 0.07 [by M. Banner et al., Phys. Rev. Lett. 28, 1597 (1972)] and 1.00 ± 0.06 [by M. Holder et al., Phys. Lett. 40B, 141 (1972)].

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The phase and magnitude of the CP-nonconservation parameter η_{+-} have been determined from the proper-time distribution of $K^0 \to \pi^+\pi^-$ decays in a short-lived neutral beam. We find $\varphi_{+-} = 41.7° \pm 3.5°$ and $|\eta_{+-}| = (2.27 \pm 0.12) \times 10^{-3}$.

The measurement of φ_{00} and $|\eta_{00}|$ reported in the preceding Letter[1] required a detailed understanding of the short-lived neutral beam and of the properties of the experimental apparatus. Our study of $K^0 \to \pi^+\pi^-$ decays in the same apparatus used in the $2\pi^0$ experiment has resulted in values of φ_{+-} and $|\eta_{+-}|$ in agreement with previous experiments, lending confidence in our ability to measure these sensitive parameters accurately and without bias. The large number of $\pi^+\pi^-$ decays probe features common to the two experiments but not visible in the less well-resolved $2\pi^0$ data. The crucial comparison of the phase and magnitude of η_{00} and η_{+-} is better made in a single experiment under the same conditions and free of common systematic errors.

The experimental arrangement is shown in the preceding Letter.[1] The event trigger required that charged particles pass through the spectrometer, one on each side of the beam, producing exactly two hits in each of the ten proportional wire chambers (PWC's). Triggers from the copious $\Lambda^0 \to \pi^- p$ decays were reduced by means of a small scintillation counter positioned near the beam to catch the forward high-momentum proton characteristic of these decays. Most events containing muons were removed by a plane of counters placed behind 4 ft of steel at the rear of the apparatus.

Three-quarters of the triggers were found to contain two complete particle trajectories emanating from a well-defined vertex. All spatial distributions and resolution functions were described in detail by a Monte Carlo simulation. The complete two-body mass spectrum, including both inbending and outbending events, is shown in Fig. 1(a). A sample of inbending $\pi^+\pi^-$ data with proper time $\tau \sim 9\tau_S$ (τ_S is the K_S lifetime) is shown in Fig. 1(b). The mass of a $K^0 \to \pi^+\pi^-$ decay was measured to 9 MeV/c (1 standard deviation) and the kaon direction was determined to 2 mrad. The full data sample includes 900 000 inbending $\pi^+\pi^-$ decays with momenta between 6 and 16 GeV/c, covering the proper-time range $4\tau_S < \tau < 18\tau_S$. About 540 000 events were recorded with the apparatus in its most forward position while 360 000 events were accumulated with the apparatus rolled 40 in. downstream.

Lambda decays were easily identified because the positively charged secondary (the proton) had a momentum at least three times that of the negatively charged particle; events whose π-p effective mass fell within 15 MeV of the lambda mass were removed. The three-body decays $K^0 \to \pi^+\pi^-\pi^0$