CPT Tests in the Neutral Kaon System

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Fermilab experiment E773 has measured the phases $\Phi_{+-} = 43.53° \pm 0.97°$ and $\Phi_{00} - \Phi_{+-} = 0.62° \pm 1.03°$ of the *CP* violating parameters η_{+-} and η_{00} from interference in the decay of neutral kaons into two charged or neutral pions from a pair of regenerators. New measurements of the K_L-K_S mass difference and the K_S lifetime are also given. These results test *CPT* symmetry and show no evidence for a violation.

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CPT symmetry in particle physics follows from very general assumptions [1]; nevertheless, continued experimental tests are warranted. While *C*, *P*, and *CP* symmetry violations are established, no violation of *CPT* has been reported. The neutral kaon system has provided very stringent tests of *CPT*; the two most precise of these are presented in this Letter.

CP violation is parametrized by the measurable ratios of decay amplitudes:

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = |\eta_{+-}|e^{i\Phi_{+-}}, \qquad (1)$$

with a similar expression for η_{00} in $\pi^0\pi^0$ decays. If *CPT* is not violated, one can show [2] that

$$\Delta\Phi = \Phi_{00} - \Phi_{+-} \approx 0. \qquad (2)$$

In addition, excluding unexpectedly large *CP* violation in decays other than $\pi\pi$, it also follows that [2]

$$\Phi_{+-} \approx \Phi_{\rm SW} \equiv \arctan\frac{2\Delta m}{\Delta\Gamma}, \qquad (3)$$

where $\Delta m = m_L - m_S$ and $\Delta\Gamma = \Gamma_S - \Gamma_L$ are the mass and decay width differences of K_L and K_S.

In Fermilab experiment E773, two K_L beams struck two different regenerators. Downstream of its regenerator, each beam is a coherent superposition $|K_L\rangle + \rho|K_S\rangle$. Here, ρ is the forward regeneration amplitude, which depends on the kaon momentum and the composition of the regenerator. The decay rate into two pions is

$$R(t) \propto |\rho e^{-it(m_S - i\Gamma_S/2)} + \eta e^{-it(m_L - i\Gamma_L/2)}|^2, \qquad (4)$$

where t is the proper time of the decay relative to the end of the regenerator. By measuring the decay rates into both neutral and charged pions, the phases $\Phi_\rho - \Phi_{+-}$ and $\Delta\Phi$ can be extracted from the interference terms. In addition, one can determine Δm and $\tau_S = 1/\Gamma_S$ (Γ_L is sufficiently well known). The regeneration amplitude ρ is proportional to $(f - \overline{f})/k$, the difference of the nuclear scattering amplitudes. In our energy range, $|(f - \overline{f})/k|$ follows, to a good approximation, a power law in the kaon momentum $p = \hbar k$, and its phase is determined though a dispersion relation $(f - \overline{f})/k \propto p^{\alpha-1}\exp[-i\pi(1+\alpha)/2]$. Elsewhere [3] the uncertainty in the extraction of the phase Φ_ρ of the regeneration amplitude from its momentum dependence is treated. This Letter, then, reports on both tests (2) and (3) of *CPT* symmetry.

E773 took data for three months in the 1991 fixed-target run at Fermilab. The apparatus (Fig. 1) was essentially the same as for the 1987–88 run (experiment E731 [4]) and is described in more detail elsewhere [5]. The two K_L beams were produced by 800 GeV protons striking a beryllium target. The detector components were located between 115 and 190 m downstream of the target. The regenerators, which were made of plastic scintillator

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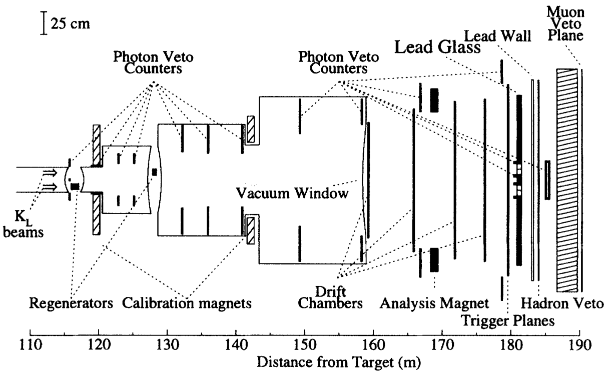

FIG. 1. Schematic of the Fermilab E773 detector.

($CH_{1.1}$), were placed at 117 m (the upstream regenerator, UR) and at 128 m (the downstream regenerator, DR). The UR (DR) was 1.2 (0.4) interaction lengths long. The regenerator lengths and locations were chosen to allow cross-checks of the results from the different interference patterns. They toggled between the two beams once every minute. The DR was fully active (every block was viewed by two phototubes), while only $\frac{1}{4}$ of the UR blocks were instrumented. Every block was 3.3 cm in the beam direction; the off-line cut on each was 0.2 (0.8) minimum-ionizing equivalents for the DR (UR). This vetoed almost all inelastic interactions.

The decay region for each beam extended from its regenerator to the end of the vacuum tank at 159 m. Photon vetoes for detecting particles leaving the fiducial region were located at 13 different positions inside the vacuum tank and throughout the spectrometer. The spectrometer consisted of four drift chambers and one magnet; its resolution was $\sigma_p/p = 0.50[1 \oplus p/(40 \text{ GeV}/c)]\%$. After the last chamber there were two trigger scintillator hodoscopes with horizontal and vertical segmentation. Following these was a circular array of 804 lead glass blocks (each 5.8 cm $\times$ 5.8 cm $\times$ 18.7 radiation lengths deep) with two beam holes. The energy resolution varied from 3% to 6% depending on photon energy and location.

The trigger for the two-body charged decays $K \to \pi^+\pi^-$ required hits on both sides of the horizontal and vertical center lines of the drift chambers and hodoscopes (with some overlap allowed). For part of the run (set 1) there were other trigger planes at 141 m; these were removed after the drift chamber trigger was improved, increasing the charged-mode decay volume (set 2). The neutral trigger required at least 25 GeV and four or six clusters (for $2\pi^0$ and $3\pi^0$ decays) of energy in the calorimeter.

$K \to \pi^+\pi^-$ events (charged mode) were required to have two good tracks. Vertex quality and aperture cuts were applied. The ratio of cluster energy to spectrometer momentum had to be less than 0.8 to reject electrons from $K \to \pi e \nu$. A minimum momentum requirement of 7 GeV/c ensured that a muon would have penetrated a muon filter (located after the calorimeter) and fired a veto plane behind it. The $\pi^+\pi^-$ mass was required to be within 14 MeV/c^2 of the kaon mass; events with a $p\pi$ mass within 6 MeV/c^2 of the Λ mass were rejected. Kaons that scattered in the regenerator were discarded if their transverse momentum squared (p_T^2) was larger than 250 MeV^2/c^2. After all cuts, the background was small (0.2% and 0.8% for the UR and DR, respectively) and was dominated by scattered $K \to \pi^+\pi^-$ events.

For $K \to \pi^0\pi^0$ decays (neutral mode), the best pairing of the four clusters gave the decay vertex, assuming two π^0's and a good pairing χ^2. Further requirements reducing the $K \to \pi^0\pi^0\pi^0$ background were $\pi^0\pi^0$ mass between 474 and 522 MeV/c^2, no substantial energy in the photon vetoes, and electromagnetic cluster shapes consistent with single photons. Events with significant out-of-time energy in the calorimeter were also rejected. Kaons which scattered in the regenerators usually landed outside the profiles of the beams. For each event there were two "ring numbers," defined as $4\max[(x_E - x_C)^2, (y_E - y_C)^2]$, where the subscript E (C) refers to the location of the center of energy (center of the given beam). These served to identify scattered kaons, as seen in Fig. 2.

The remaining background to the neutral mode had three different sources. $K_L \to \pi^0\pi^0\pi^0$ events with two photons escaping detection or overlapping were simulated and subtracted; the background fraction was 0.7% (1.3%) for the UR (DR). All significant characteristics of this background were reproduced by the simulation.

Background from beam interactions in the vacuum windows, regenerators, and air around the regenerators was small, $\sim$0.1% for each regenerator.

The largest background was the residual from kaons scattered by the regenerators. To estimate the amount remaining after the ring number cut, a Monte Carlo simula-

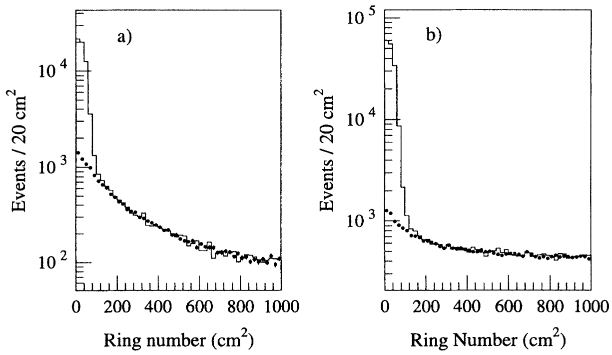

FIG. 2. Ring number distributions of $K \to \pi^0\pi^0$ for the (a) downstream and (b) upstream regenerators. Shown are the data (histogram) and a Monte Carlo simulation (dots) of the background from scattered kaons. The cut was at 120 cm^2.

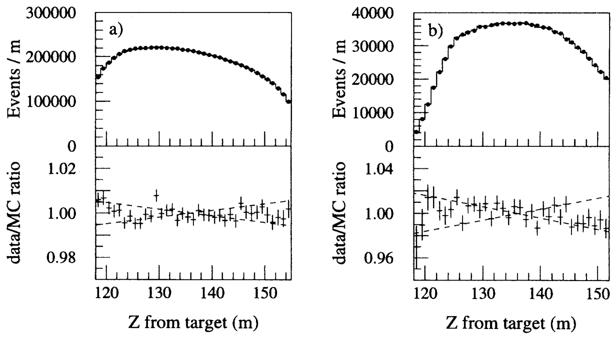

FIG. 3. Decay distributions for (a) $K_L \to \pi e \nu$ and (b) $K_L \to 3\pi^0$ decays behind the UR in set 2. The upper plots show data (histogram) and Monte Carlo results (dots), while the lower plots show the ratio of data over Monte Carlo results. Lines in each ratio plot show the possible acceptance error used in estimating systematic uncertainties. DR events showed consistent behavior.

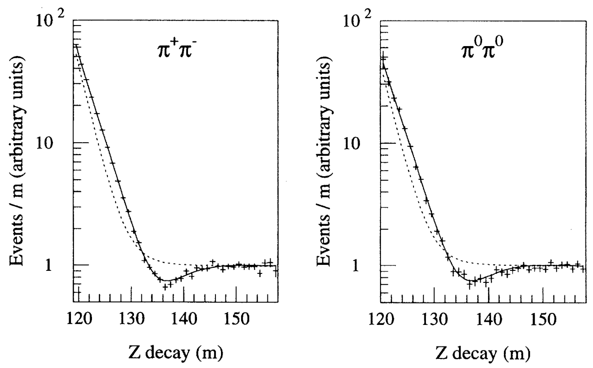

FIG. 4. Background-subtracted, acceptance-corrected decay distributions of $K \to \pi^+\pi^-$ (set 2) and $K \to \pi^0\pi^0$ (sets 1 and 2) for upstream regenerator events in the energy bin 40–50 GeV (crosses) and the predictions from the fits with (solid line) and without (dotted line) the interference term.

tion of the scattering was used (see Fig. 2). The input to the simulation was taken from the well-determined kaon p_T^2 distributions for $K \to \pi^+\pi^-$. The background fractions were 2.6% for the UR and 9.0% for the DR.

Understanding the acceptance of the detector for $K \to \pi\pi$ was crucial for this analysis. It was checked by comparing the data with Mote Carlo distributions for high-statistics samples of K_L decays into $3\pi^0$ and $\pi e \nu$ (Fig. 3). These decay modes were not sensitive to the regeneration parameters and provided a powerful check of our understanding of the detector. Monte Carlo simulations included an overlay of accidental activity when relevant.

Figure 4 shows the background-subtracted and acceptance-corrected decay distributions for $K \to \pi^+\pi^-$ and $K \to \pi^0\pi^0$ for one energy bin. The interference between K_L and K_S decays is clearly visible. Table I gives the final event totals.

The charged mode data were used to extract τ_S, Δm, and Φ_{+-}. Decay spectra from kaons with energies between 20 and 160 GeV and vertices from 118.5 m (130.0 m) to 154 m for the UR (DR) were fit in 10 GeV by 2 m bins. For set 1, fit was restricted to 140 m. In the fits, performed simultaneously to both regenerators in both data sets, the power law exponent α and the scattering amplitude $|(f - \bar{f})/k|$ at 70 GeV were floated. A total of five parameters described the normalizations

TABLE I. Background-subtracted event totals used in fits.

Sample	UR set 1	DR set 1	UR set 2	DR set 2
Charged mode	333 272	70 707	573 241	152 870
Neutral mode	70 362	24 438	146 869	50 504

and common energy dependence of the kaon flux on the two regenerators in the two data sets. Our choice of fits is motivated by the PDG [6] treatment of the measurements of Ref. [4].

We extract τ_S by setting $\Phi_{+-} = \Phi_{SW}$ [Eq. (3)] and floating Δm. Our result is

$$\tau_S = [0.8941 \pm 0.0014(\mathrm{stat}) \pm 0.0009(\mathrm{syst})] \times 10^{-10}\,\mathrm{s}\,.$$

For all subsequent fits, to reduce possible biases, we fix τ_S to the world average from the PDG [6]: $(0.8926 \pm 0.0012) \times 10^{-10}$ s.

In fitting for Δm, we float Φ_{+-}, with which Δm is strongly correlated. We find

$$\Delta m = [0.5297 \pm 0.0030(\mathrm{stat}) \pm 0.0022(\mathrm{syst})] \times 10^{10}\hbar\,\mathrm{s}^{-1}.$$

This result is consistent with the value [6,7] from E731: $(0.5257 \pm 0.0049) \times 10^{10}\hbar\,\mathrm{s}^{-1}$. The weighted average of our two measurements is $(0.5282 \pm 0.0030) \times 10^{10}\hbar\,\mathrm{s}^{-1}$; this is nearly 2 standard deviations lower than the average of the other three results used by the PDG [6]. Note that the E731 result for Δm was dominated by $K \to \pi^0\pi^0$ decays, while this analysis uses only $K \to \pi^+\pi^-$ decays. A lower value of Δm brings previous measurements of Φ_{+-} into agreement with the expectation based on *CPT* invariance shown in Eq. (3) [4,6].

To determine Φ_{+-}, we fix Δm to the combined E731-E773 value given above. The result is

$$\Phi_{+-} = 43.53^\circ \pm 0.58^\circ(\mathrm{stat}) \pm 0.49^\circ(\mathrm{syst})\,.$$

The result changes by -0.33° (0.52°) when τ_S (Δm) is increased by 0.0012×10^{-10} s $(0.0030 \times 10^{10}\hbar$ s). The total error, including the τ_S and Δm dependences, is then 0.97°. The next most precise result is from E731: $42.5^\circ \pm 1.2^\circ$; the central value [8] has been adjusted to consistent τ_S and Δm values, and the systematic error is correlated with that of the current experiment [9]. We agree well with $\Phi_{SW} = 43.37° \pm 0.17°$ ($43.64° \pm 0.17°$) derived from the PDG τ_S value and our (PDG) Δm.

The charged-mode fits have a reduced χ^2 of 1.06 for 621 or 622 degrees of freedom. Correcting for hydrogen [10] in the scintillator, the nuclear scattering amplitude for carbon is $|(f - \bar{f})/k| = 1.21 \pm 0.01$ mb at 70 GeV/c and varies as $p^{-0.572\pm0.007}$. Table II lists the systematic sources considered.

The fit determining $\Delta\Phi$ is similar to the Φ_{+-} fit. In addition, $\Delta\Phi$, $|\eta_{+-}/\eta_{00}|$, and normalizations for the number of $\pi^0\pi^0$ to $\pi^+\pi^-$ events in the two data sets are floated. Two parameters (found consistent with zero) for a possible energy dependence of the relative neutral to charged mode acceptance are also added. For the neutral mode the decay region extended from 120 m (130 m) to 152 m for the UR (DR) in 2 m bins and the energy range was from 40 to 150 GeV in 10 GeV bins. We find

$$\Delta\Phi = 0.62° \pm 0.71°(\text{stat}) \pm 0.75°(\text{syst}),$$

using the same values for τ_S and Δm as in the Φ_{+-} fit. The χ^2 was 1192 for 1150 degrees of freedom. This result ($0.62° \pm 1.03°$) is consistent with zero and is insensitive to the values of Δm and τ_S used (<0.03° for one standard deviation). It is consistent with that from E731 ($-1.7° \pm 1.2°$) [4] and NA31 ($0.2° \pm 2.9°$) [11]. (Central values have been adjusted for τ_S and Δm dependences). Averaging the E731 and E773 values (accounting for correlated systematics from the calorimeter) yields $\Delta\Phi = -0.30° \pm 0.88°$.

The systematic error for this measurement is dominated by uncertainties in the modeling of the calorimeter. The absolute energy scale was fine tuned by comparing the sharp edge in the Monte Carlo and data z distributions of $K \to \pi^0\pi^0$ and $K \to 3\pi^0$ near the regenerators. The 0.08% uncertainty in the scale led to a $\pm 0.45°$ error in $\Delta\Phi$. The error contribution due to the nonlinear response of the calorimeter was estimated at 0.3°; uncertainties in the calorimeter resolution added 0.2°. Further contributions include the simulation of the background (0.4°), neutral mode acceptance (0.2°), and charged mode acceptance (0.15°).

A fit to neutral-mode data alone for Δm and τ_S gave results consistent with those from the charged-mode fits; the statistical power gained by adding the neutral-mode data, however, did not compensate for the additional contribution to the systematic error. The regeneration parameters were consistent in charged- and neutral-mode fits. The UR alone gave the best statistical precision (see Table I); all quantities were consistent when fitting the data from each regenerator separately.

In summary, we find that $\Delta\Phi$ is consistent with zero and that our values of Φ_{SW} and Φ_{+-} agree, consistent with *CPT* symmetry. These results may be combined to limit the K^0-$\bar{K}^0$ mass difference [2], yielding

$$\frac{|m_{K^0} - m_{\bar{K}^0}|}{m_{K^0}} \simeq \frac{2\Delta m}{m_{K^0}} \frac{|\eta_{+-}|}{\sin\Phi_{SW}} \times |\Phi_{+-} - \Phi_{SW} + \Delta\Phi/3| < 1.3 \times 10^{-18}$$

at the 90% C.L.

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TABLE II. Systematic error estimates for the charged-mode fits. The individual sources were added in quadrature to give the total error.

	Φ_{+-} fit (deg)	Δm fit ($10^{10}\hbar$/s)	τ_S fit (10^{-10}s)
Regenerator positions, sizes	0.10	0.0010	0.0003
Acceptance	0.30	0.0008	0.0006
Background subtr.	0.15	0.0010	0.0003
Regeneration phase [3]	0.35	0.0008	0.0006
τ_S dependence	—	0.0012	—
Total	0.49	0.0022	0.0009

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