

Test of *CPT* Symmetry through a Determination of the Difference in the Phases of η_{00} and η_{+-} in $K \rightarrow 2\pi$ Decays

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Data collected by the E731 experiment at Fermilab were used to search for *CPT* violation in $K^0 \rightarrow \pi\pi$ decays by measuring the difference $\Delta\phi$ between the phases of the *CP*-violating parameters η_{00} and η_{+-} . Our result, $\Delta\phi = -0.3^\circ \pm 2.4^\circ \pm 1.2^\circ$, where the first error is statistical and the second systematic, is consistent with *CPT* symmetry.

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CPT symmetry is a natural consequence of local quantum field theory¹ and guarantees the equality of masses and lifetimes of particles and antiparticles. It is conceivable, however, that a small violation of *CPT* symmetry could occur in extensions of quantum field theory (e.g., string theory²); thus, it is imperative to check *CPT* symmetry wherever possible. The neutral-kaon system provides some of the most sensitive tests of *CPT* symmetry. The ratio of the decay amplitudes $\eta \equiv \text{amp}(K_L \rightarrow \pi\pi) / \text{amp}(K_S \rightarrow \pi\pi)$ can be written as³ $\eta_{+-} \equiv |\eta_{+-}| e^{i\phi_{+-}} = (\epsilon - \Delta + a) + \epsilon'$ for the $\pi^+\pi^-$ final state and $\eta_{00} \equiv |\eta_{00}| e^{i\phi_{00}} = (\epsilon - \Delta + a) - 2\epsilon'$ for the $\pi^0\pi^0$ final state (Fig. 1). Here ϵ is a measure of *CP* violation without *CPT* violation in K^0 - \bar{K}^0 mixing, and Δ is similarly a measure of *CPT* violation without *T* violation. Direct *CP* and *CPT* violations in the decay amplitudes are parametrized by $a \equiv (A_0 - \bar{A}_0) / (A_0 + \bar{A}_0)$ (chosen to be real⁴) and

$$\epsilon' = \frac{1}{\sqrt{2}} \frac{A_2 - \bar{A}_2}{A_0 + \bar{A}_0} e^{i(\delta_2 - \delta_0)}, \quad (1)$$

where A_I (\bar{A}_I) is the 2π decay amplitude of K^0 (\bar{K}^0) to isospin- I final state with corresponding phase shift δ_I from final-state interactions. *CPT* symmetry results in two constraints that can be tested by experiment: First, *CPT* symmetry implies that the phase of $2\eta_{+-} + \eta_{00}$ be within a few degrees of the "natural angle" $\phi_\epsilon \equiv \arg(\Gamma_S/2 + i\Delta m) = 43.7^\circ \pm 0.2^\circ$, where Γ_S is the K_S

decay rate and $\Delta m \equiv M_{K_L} - M_{K_S}$. Second, using the experimental value⁵ $\delta_2 - \delta_0 = -45^\circ \pm 10^\circ$ in Eq. (1), the *CPT* relation $\bar{A}_I = A_I^*$ leads to $\arg \epsilon' \approx \phi_\epsilon$. This, together with the current knowledge^{6,7} of $|\text{Re}(\epsilon'/\epsilon)|$, requires the phase difference $\Delta\phi \equiv \phi_{00} - \phi_{+-}$ to be much less than 1° . With the accepted value⁸ of $\phi_{+-} = 44.6^\circ \pm 1.2^\circ$,

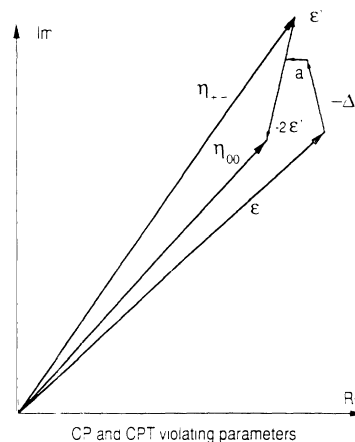


FIG. 1. Relationship among the *CPT*-violating parameters a , Δ , and the directly measurable quantities η_{+-} , η_{00} . Since *CPT* symmetry predicts ϵ' to be parallel to ϵ , a nonzero value of $\Delta\phi = \phi_{00} - \phi_{+-}$ also indicates *CPT* violation. The magnitudes of a , Δ , and ϵ' are exaggerated for clarity.

however, the most recent published measurement⁹ of $\phi_{00} = 55.7^\circ \pm 5.8^\circ$ corresponds to a phase difference about 2 standard deviations away from the prediction of *CPT* symmetry;¹⁰ this has generated considerable interest and speculation.³

$$\frac{d^2 I_{\pi\pi}}{dP_K dt} \propto F(P_K) e^{-X} [|\rho|^2 e^{-t/\tau_S} + |\eta|^2 e^{-t/\tau_L} + 2|\rho||\eta| e^{-t/2\tau_S} \cos(\Delta m t + \phi_\rho - \phi_\eta)], \quad (2)$$

where τ_S (τ_L) is the K_S (K_L) lifetime, Δm the mass difference between K_L and K_S , $\rho = |\rho| e^{i\phi_\rho}$ the coherent regeneration amplitude, and $F(P_K)$ the incident kaon momentum spectrum. The incident flux is normalized to the other vacuum beam whose $\pi\pi$ rate is simply $F(P_K) \times |\eta|^2 e^{-t/\tau_L}$. The factor e^{-X} accounts for absorption in the regenerated beam. As can be inferred from Eq. (2), the values extracted for ϕ_{+-} and ϕ_{00} individually depend on ϕ_ρ and Δm , but the difference $\Delta\phi \equiv \phi_{00} - \phi_{+-}$ is insensitive to both parameters.

A description of the experimental setup can be found in Refs. 6 and 11, and only a brief account of the essential features is given here. The $\pi^0\pi^0$ decays were detected with a lead-glass calorimeter having an energy resolution for photons of $2.5\% + 5\%/\sqrt{E}$ (E in GeV). The $\pi^+\pi^-$ decays were reconstructed using a magnet and a sixteen-plane drift-chamber system with a typical momentum resolution of 1%. All four decay modes, $K_{S,L} \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$, were collected simultaneously and the regenerator alternated frequently between the two beams. This minimizes sensitivity to differences in intensity and momentum spectrum between the beams as well as to reconstruction inefficiencies, dead-time effects, and calibration changes with time.

The phase-difference result presented here is based on the same data set that was recently used to determine $\text{Re}(\epsilon'/\epsilon)$,⁶ and the event-reconstruction and background-subtraction techniques employed are the same as for that analysis. For neutral decays, however, the length of the decay region is extended downstream by 13 m to increase sensitivity to the phase in the interference term. Most of the phase information is provided by decays at the lower end of the energy range where a larger proper-time region can be sampled. For $\pi^+\pi^-$ decays, the length of the decay region is 14 m (6.5 K_S lifetimes at 40 GeV), and for $\pi^0\pi^0$ decays, it is 29 m (14 K_S lifetimes at 40 GeV). It is not possible to extend the decay region for the charged mode since it is hardware defined by a thin trigger hodoscope.

The $2\pi^0$ mass distribution for the regenerated beam has a small (0.04%) background which is dominated by $3\pi^0$ decays from the K_L beam transmitted through the regenerator. A $3\pi^0$ decay can fake a $2\pi^0$ signal when two out of the six photons are lost either by escaping the detector or by merging with other photons in the lead-glass calorimeter. Figure 2 shows the vertex distributions for signal and backgrounds in the regenerated beam. For the vacuum beam, the level of $3\pi^0$ back-

ground is higher (0.99%); its vertex distribution has the same shape as that of the regenerated beam. Another source of background arises from incoherently produced kaons that emerge with nonzero scattering angle from the regenerator. This amounts to 2.7% in the regenerated beam, and its vertex distribution is also shown in Fig. 2. The corresponding background level for the vacuum beam is 2.8%. There is also a background due to nuclear interactions at the regenerator ($z = 123$ m) and at the 2-mm-thick trigger hodoscope ($z = 138$ m). In the charged mode, the background in the vacuum beam (0.32%) is dominated by K_{e3} decays, whereas the background in the regenerated beam (0.13%) comes from incoherent regeneration.

In order to extract $\phi_{+-} - \phi_\rho$ and $\phi_{00} - \phi_\rho$ from the shapes of the vertex distributions in the regenerated beam, the acceptance as a function of decay vertex must be well understood. Accurate knowledge of the accep-

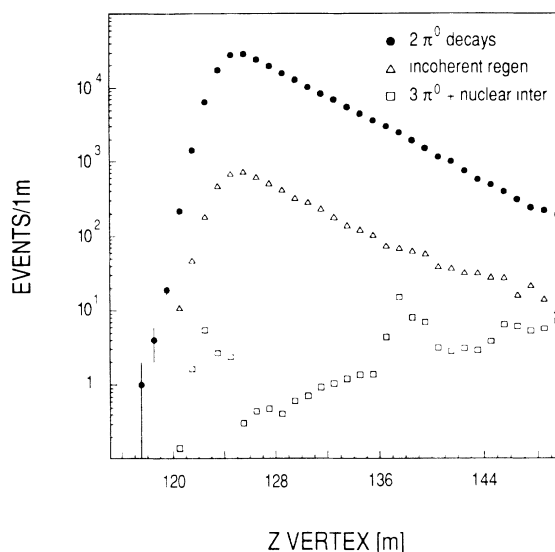


FIG. 2. The vertex distribution of reconstructed $2\pi^0$ decays in the regenerated beam together with the background contributions from incoherently regenerated K_S (triangles) and $3\pi^0$ decays and nuclear interactions (squares). The incoherent background under the coherent peak is measured from the data by the extrapolation to zero scattering angle (see text). The $3\pi^0$ + nuclear interaction backgrounds are estimated by the fit of the mass distribution where the $3\pi^0$ component is obtained from the Monte Carlo simulation.

tance is essential for the determination of $\text{Re}(\epsilon'/\epsilon)$, and is discussed in detail in Ref. 6. The fit is done by comparing the background-subtracted and acceptance-corrected z distributions with the predicted rate $I_{\pi\pi}$ of Eq. (2), constrained by the total number of events in the vacuum beam. In the fit for ϕ_{+-} and ϕ_{00} , the kaon parameters τ_S , τ_L , and Δm are fixed to their world-average values.⁸ The parameter $\text{Re}(\epsilon'/\epsilon)$, which is a measure of the difference in magnitude between η_{+-} and η_{00} , is allowed to float in the fit.¹² The assumptions made for the regeneration amplitude¹³ are the following: (a) The difference in the forward-scattering amplitudes¹⁴ between K^0 and \bar{K}^0 has a power-law dependence on the kaon momentum; namely, $|(f-\bar{f})/k| \propto P_K^{-\alpha}$; (b) the phase of $(f-\bar{f})/k$ is given by the analyticity condition $\arg[(f-\bar{f})/k] = -(2-\alpha)\pi/2$. The absorption factor e^{-X} is measured to better than 1% of itself from $K_L \rightarrow \pi^+\pi^-\pi^0$ and $K_L \rightarrow \pi^0\pi^0\pi^0$ decays in the two beams. This uncertainty has a negligible effect on $\Delta\phi$.

The result of the fit is $\phi_{+-} = 47.7^\circ \pm 2.0^\circ$, $\phi_{00} = 47.4^\circ \pm 1.4^\circ$, and $\Delta\phi \equiv \phi_{00} - \phi_{+-} = -0.3^\circ \pm 2.4^\circ$. The errors are statistical and $\chi^2 = 316$ for 340 degrees of freedom. Figure 3 shows the quality of the fit to the data for both modes. As a check of our understanding of the acceptance, we have also fitted for τ_S and Δm , and we have obtained $\tau_S = (0.8882 \pm 0.0030) \times 10^{-10}$ s (charged mode), $\tau_S = (0.8929 \pm 0.0033) \times 10^{-10}$ s (neutral mode), $\Delta m = (0.5377 \pm 0.0098) \times 10^{10} \hbar \text{ s}^{-1}$ (both modes combined), where the errors are statistical only. These results are in good agreement with the corresponding world averages.⁸

The systematic errors on $\Delta\phi$ come from various sources. When the parameters τ_S and Δm are varied by 1 standard deviation around their world-average values, the value of $\Delta\phi$ changes by 0.2° for τ_S and 0.1° for Δm . Similarly the value of $\Delta\phi$ changes by $+0.8^\circ$ for a change of $+10^{-3}$ on $\text{Re}(\epsilon'/\epsilon)$. The acceptance was carefully studied using high-statistics modes ($10^7 K_{e3}$ events for charged mode and $6 \times 10^6 3\pi^0$ for neutral mode). The remaining uncertainty in the acceptance corresponds to an error in $\Delta\phi$ of 0.9° . The uncertainty in the absolute energy calibration (0.1%) is determined from the sharp upstream edge of the decay distribution in the regenerated beam. The resulting error in $\Delta\phi$ is 0.6° . The subtraction of the $3\pi^0$ and incoherent backgrounds in neutral mode contributes an error of 0.3° . Accidental overlaps in the detector have a negligible effect on the result. The combined systematic error on $\Delta\phi$ is thus 1.2° . Excluding the regeneration phase uncertainty, the systematic error on ϕ_{+-} is 0.9° (dominated by acceptance uncertainty) and the systematic error on ϕ_{00} is 0.8° (dominated by absolute energy calibration).

The final result is then $\Delta\phi \equiv \phi_{00} - \phi_{+-} = -0.3^\circ \pm 2.4^\circ$ (stat) $\pm 1.2^\circ$ (syst). This result is consistent with zero and thus with the prediction of CPT symmetry. With the world average of ϕ_{+-} , our measurement of $\Delta\phi$

leads to a value for $\arg(2\eta_{+-} + \eta_{00})$ of $44.5^\circ \pm 1.5^\circ$, which is well within 1 standard deviation of the natural angle $\phi_\epsilon = 43.7^\circ$. Our measurement of ϕ_{+-} is consistent with the world average. This supports the assumptions made for the regeneration amplitude in the fit. In conclusion, our measurement shows no indication of CPT violation. Further confirmation is provided by a recent experiment¹⁵ which finds $\Delta\phi = 0.2^\circ \pm 2.9^\circ$.

The limit on $\Delta\phi$ also leads to a limit on the component of ϵ' perpendicular to ϵ using the relation $\text{Im}(\epsilon'/\epsilon) = -\Delta\phi/3$ which can be easily seen from Fig. 1. With the measured value of $\Delta\phi$, we obtain a 95%-confidence limit on $\text{Im}(\epsilon'/\epsilon)$ without any assumption of CPT invariance: $-0.03 < \text{Im}(\epsilon'/\epsilon) < 0.03$.

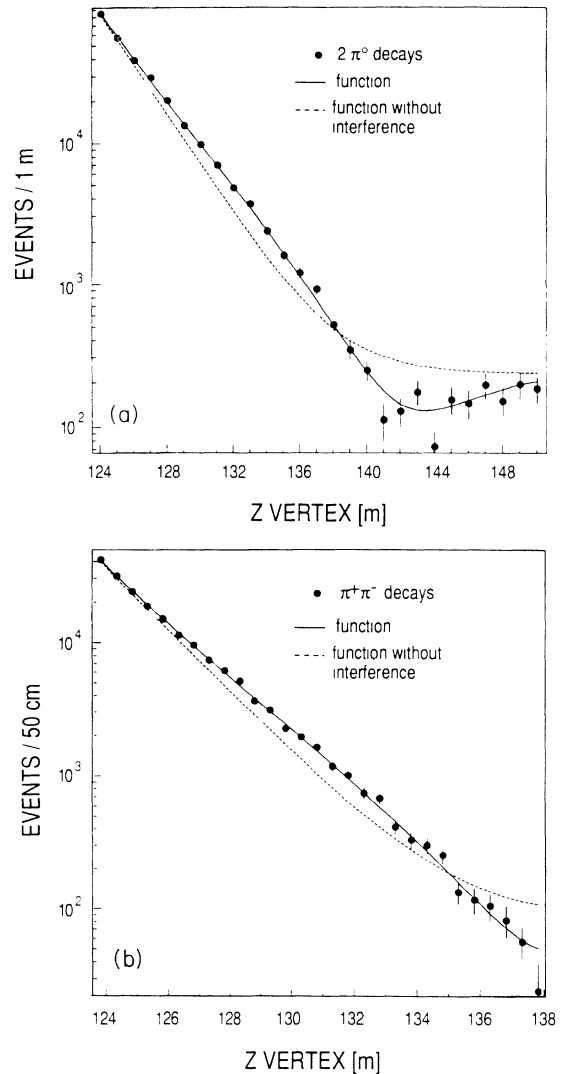


FIG. 3. The vertex distributions in the regenerated beam after background subtractions and acceptance corrections for the (a) neutral and (b) charged modes. The solid curves are the result of the fit described in the text. The momentum cuts on the kaon energy are (a) [40,50] GeV and (b) [30,40] GeV.

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⁴The relative phase of K_0 and \bar{K}_0 is chosen such that

$\arg A_0 = \arg \bar{A}_0$ (Wu-Yang phase convention).

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¹⁰The discrepancy between $\arg(2\eta_{+-} + \eta_{00})$ and ϕ_ϵ is also about 2σ if it is assumed that the $\Delta S = \Delta Q$ rule holds and that there is no anomalously large CP or CPT violations in $3\pi^0$ and semileptonic modes; Barmin *et al.*, Ref. 3.

¹¹For a detailed discussion of the analysis, see the M. Karlsson, Ph.D. thesis, Princeton University, 1990.

¹²In the determination of $\text{Re}(\epsilon'/\epsilon)$ in Ref. 6, the phase difference was fixed at zero. The value obtained for $\text{Re}(\epsilon'/\epsilon)$ in this analysis is consistent with that given in Ref. 6.

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¹⁴The regeneration amplitude ρ is related to $(f - \bar{f})/k$ by $\rho = \pi i N L g (f - \bar{f})/k$, where N is the density of scatterers, L is the length of the regenerator, and $g = (1 - e^{-x})/x$ is a geometrical factor with $x = (\frac{1}{2} - i\Delta m/\Gamma_S)L/\Lambda_S$ with Λ_S the K_S decay length. For a thin regenerator g is unity, and $|g - 1|$ is always less than 0.2 in our case.

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