



CPT RESULTS FROM KTeV

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I present^a several preliminary measurements from KTeV^b of the fundamental neutral K parameters, and their implications for CPT violation. A new limit is given on the sidereal time dependence of ϕ_{+-} . The results are based on data collected in 1996-97.

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1 Introduction

Neutral kaons have long been recognized as a superb laboratory for the study of CPT symmetry. The K_L wavefunction is a coherent superposition of a particle and antiparticle:

$$K_L \sim (1 + \epsilon_L)K^0 - (1 - \epsilon_L)\bar{K}^0 \quad (1)$$

The powerful probe of CPT symmetry originates from this coherent superposition. There is also a fortunate conspiracy of the kaon masses, lifetimes, and decay widths, allowing one to look experimentally for very small CPT violating effects that may be present. While many probes in the neutral kaon sector are available, I will mention only ones relevant to KTeV. Table 1 shows the experimental observables (and their definitions) that are sensitive to possible CPT violating effects.

The traditional framework to parameterize possible neutral kaon CPT violation can be found in the literature^{1,2,3}. It is a phenomenological approach: one which spells out all possible CPT effects without much consideration to the microscopic details of the theory. Nevertheless, one can derive the experimental signatures that would imply CPT violation.

CPT violating effects in the $K^0 \rightarrow 2\pi$ and $\bar{K}^0 \rightarrow 2\pi$ amplitudes can reveal themselves in the $K_L \rightarrow 2\pi$ decay mode. This is possible since the latter is the *coherent superposition* of those 2 amplitudes. CPT violation of this type is called “direct” since it is tied to a decay amplitude. Indirect CPT violating effects such as the difference between M_{K^0} and $M_{\bar{K}^0}$ could be seen in the comparison of ϕ_{+-} to ϕ_{SW} . Direct CPT violating effects may also show up in the semileptonic decay modes $K_L \rightarrow e^\pm \pi^\mp \nu$ (Ke3). The two Ke3 final states,

Table 1: Experimental observables sensitive to CPT violating effects.

Observables	Definitions
$\Delta m, \tau_S$	$M_{K_L} - M_{K_S}, K_S$ lifetime
ϕ_{SW}	$\arctan \frac{2\Delta m}{\Gamma_S}$
η_{+-}, ϕ_{+-}	$\frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)}, \arg(\eta_{+-})$
η_{00}, ϕ_{00}	$\frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)}, \arg(\eta_{00})$
ϵ'	$\frac{1}{3}(\eta_{+-} - \eta_{00})$
δ_L	$\frac{BR(e^+\pi^-) - BR(e^-\pi^+)}{BR(e^+\pi^-) + BR(e^-\pi^+)}$

in the limit of $\Delta S = \Delta Q$ and CPT conservation, would measure $2Re \epsilon_L$, the CP violation in kaon mixing. Therefore, a comparison of the semileptonic charge asymmetry δ_L to the 2π observables might reveal CPT violating effects in the Ke3 or 2π decay amplitudes.

The following are CPT tests in the traditional framework:

$$\phi_{+-} - \phi_{00} \sim \frac{ReB_2}{ReA_2} - \frac{ReB_0}{ReA_0} \quad (2)$$

$$\phi_{+-} - \phi_{SW} \approx \frac{-1}{\sqrt{2}|\eta_{+-}|} \left[\frac{M_{K^0} - M_{\bar{K}^0}}{\Delta m} + \frac{ReB_0}{ReA_0} \right] \quad (3)$$

$$Re\left(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}\right) - \frac{\delta_L}{2} = Re\left(Y + X_- + \frac{ReB_0 + iImA_0}{ReA_0 + iImB_0}\right) \quad (4)$$

In the equations above, the parameters B_0 and B_2 (Y and X_-) parameterize direct CPT violating effects in the 2π (Ke3) amplitudes.

A significantly new approach called the 'standard-model-extension' has been advocated by A. Kostelecky and collaborators in recent years^{4,5,6}. It is based on a theory with spontaneously broken CPT/Lorentz symmetry, which might happen at the Planck scale in certain string and quantum gravity theories. It appears to be compatible with the basic tenets of quantum field theory, and retains the property of gauge invariance and renormalizability needed for the Standard Model.

The CPT violating phenomenology is significantly simpler than the tradi-

tional approach. The direct CPT violating effects vanish at lowest order, so that the lowest order effect appears in indirect CPT violating observables such as $M_{K^0} - M_{\bar{K}^0}$. An unexpected prediction is a Lorentz violating effect such that the observables depend on the meson momentum (γ, β) and its orientation in space.

For a fixed target experiment such as KTeV, one would have:

$$\phi_{+-} \approx \phi_{SW} + \frac{\sin\phi_{SW}}{|\eta_{+-}|\Delta m} \gamma [\Delta a_0 + \beta\Delta a_3 \cos\chi + \beta\sin\chi(\Delta a_1 \cos\Omega t + \Delta a_2 \sin\Omega t)] \quad (5)$$

The angular frequency Ω , time t , angle χ are needed to fully describe the orientation of the K_L with respect to Δa_μ , which are the Lorentz violating parameters in this theoretical framework. For KTeV, $\gamma \approx 100$ and $\cos\chi \sim 0.6$.

We present preliminary results from the data taken with the KTeV detector at Fermilab during 1996-1997. It represents half of all data collected by KTeV.

2 Beam and Detector

The KTeV beamline and detector at Fermilab have been described elsewhere in the literature⁷. For these preliminary results, the detector was configured for the measurement of $\text{Re}(\epsilon'/\epsilon)$. As shown in Fig. 1, two approximately parallel neutral K_L beams enter a long vacuum tank, which defines the fiducial volume for accepted decays. One of the beams strikes an active absorber (regenerator), which serves to tag the coherent regeneration of K_S . The regenerator position was moved to the other beam in between Tevatron spill cycles. Behind the vacuum tank, the charged decay products are analyzed by 4 planar drift chambers and an analysis magnet that imparted a 411 MeV/c horizontal transverse kick to the particles. A high precision 3100-element pure Cesium Iodide calorimeter (CsI) is used primarily to measure the energy of e^\pm and photons. Photon veto detectors surrounding the vacuum decay volume, drift chambers, and CsI serve to reject events with particles escaping the calorimeter.

3 2π Parameters

The 2π parameters τ_S , Δm , ϕ_{+-} and ϕ_{00} are extracted from data taken with the beam transmitting through the regenerator. The regenerator is “active”, allowing the suppression of all but the coherent regeneration of K_S . With coherent regeneration, the kaon wavefunction is the mixture $\rho K_S + K_L$, where ρ is the (momentum and material dependent) regeneration amplitude. Hence the 2π parameters can be extracted from the K_S - K_L interference present in

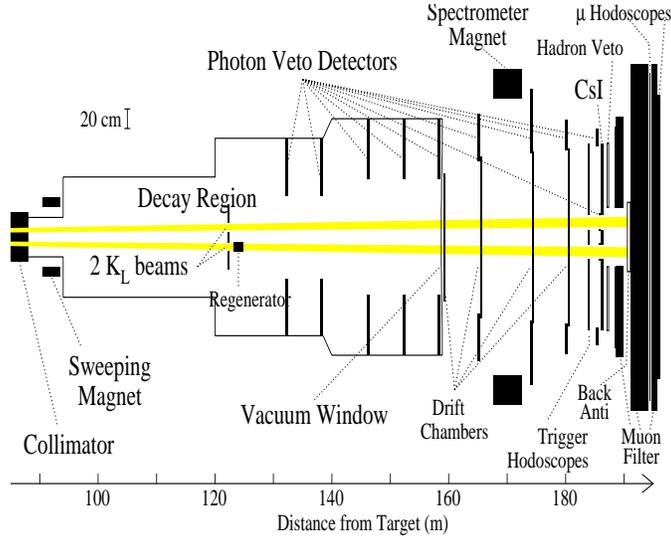


Figure 1: The KTeV detector configured for measuring $\text{Re}(\epsilon'/\epsilon)$.

the subsequent time evolution of the kaon wave function. The proper-time dependence of the 2π event rate behind the regenerator is:

$$\frac{dN_{2\pi}}{d\tau} = \left|\frac{\rho}{\eta}\right|^2 e^{-\Gamma_S \tau} + e^{-\Gamma_L \tau} + 2\left|\frac{\rho}{\eta}\right| e^{-\frac{\Gamma_S + \Gamma_L}{2} \tau} \cos(\Delta m + \phi_\rho - \phi_\eta) \quad (6)$$

Figure 2 shows the $K_L - K_S$ interference evident in the 2π event rate behind the regenerator. In practice, one has to subtract the incoherent scattering background (inelastic and diffractive), as they would have a different time evolution.

These measurements share many common systematics with the analysis of $\text{Re}(\epsilon'/\epsilon)$ in the same dataset. The latter will be detailed in an upcoming publication.^a To determine the event rate as a function of proper-time, one has to reconstruct the parent kaon momentum p_K and its decay vertex position. The determination of p_K relies on a good understanding of the detector energy scale and its nonlinearities. In addition, one has to account for the detector geometrical acceptance varying with the decay vertex position and p_K .

^aThe preliminary KTeV result from 1996-97 is $\text{Re}(\epsilon'/\epsilon) = (20.7 \pm 2.8) \cdot 10^{-4}$.

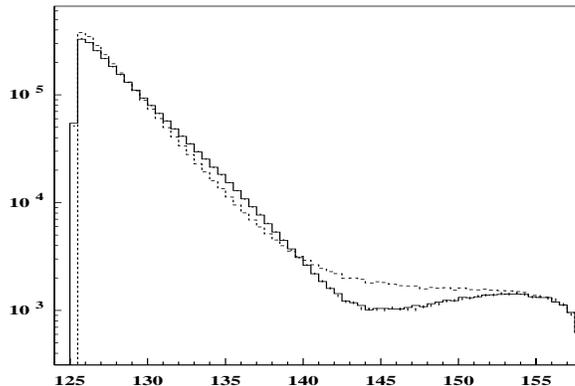


Figure 2: The 2π event rate versus distance (meters) from target for $40 < p_K < 50$ GeV. The downstream regenerator edge is located at ~ 125 meters. Solid (dashed) histogram shows prediction with (without) interference. Dots are data.

Another necessary ingredient is the understanding of the regeneration amplitude ρ . As the data contains inherently only the combination $\phi_\rho - \phi_\eta$, we need a model of ϕ_ρ in order to extract ϕ_η . Our theoretical understanding of ϕ_ρ and its dependence on p_K includes coherent scattering from lead as well as carbon^b, analyticity, nuclear screening, and attenuation.^{8,9} In the extraction of $\phi_{\eta+-}$, we assign a systematic uncertainty of 0.78° due to our understanding of ϕ_ρ . We present below a cross check of this in section 4.1.

The preliminary results are based on the entire 1996-97 KTeV and is approximately 25M $K \rightarrow 2\pi$ events in the regenerator beam.

3.1 Δm and τ_S

We perform a simultaneous fit of the data for Δm and τ_S , under the assumption of CPT symmetry. That is to say, we fit with the constraint $\phi_\eta = \phi_{SW}$. We extract a value of:

$$\tau_S = 89.67 \pm 0.03_{stat} \pm 0.04_{sys} \text{ psec} \quad (7)$$

$$\Delta m = 52.62 \pm 0.07_{stat} \pm 0.13_{sys} 10^8 \hbar s^{-1} \quad (8)$$

These are consistent with the PDG¹⁰ average at only the 2.5σ level. However, it is more consistent with the published values from the previous decade. Figure 3 shows a compilation of previous results including ours.

^bThe regenerator contains mostly plastic scintillator (i.e. carbon) and a lead converter module.

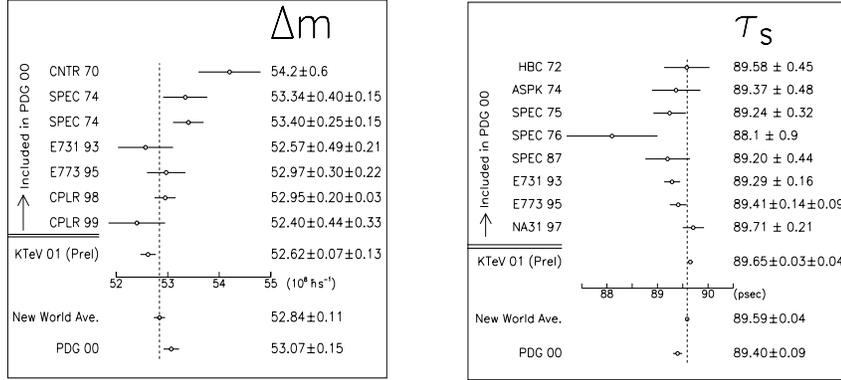


Figure 3: A compilation of Δm and τ_S values including our preliminary results.

3.2 $\phi_{+-} - \phi_{00}$

To extract $\phi_{+-} - \phi_{00}$, we perform a simultaneous fit of the data to all the 2π parameters relaxing the constraint of CPT symmetry. However, since the regeneration phase ρ is common in both the $\pi^+\pi^-$ and $\pi^0\pi^0$ mode, the phase difference is immune to the regeneration phase uncertainty. We find a phase difference that is consistent with no direct CPT violation:

$$\phi_{+-} - \phi_{00} = 0.41^\circ \pm 0.22^\circ_{stat} \pm 0.53^\circ_{sys} \quad (9)$$

3.3 ϕ_{+-} and Sidereal Time Dependence

The extraction of ϕ_{+-} and its comparison to ϕ_{SW} is the search for indirect CPT violation (i.e. it is sensitive to a nonvanishing value of $M_{K^0} - M_{\bar{K}^0}$). We fit simultaneously to Δm , τ_S , and ϕ_{+-} with no assumption of CPT symmetry, and compare it to ϕ_{SW} which was extracted under the assumption of CPT symmetry (see section 3.1). We find a value consistent with CPT symmetry:

$$\phi_{+-} = 44.11^\circ \pm 0.72^\circ_{stat} \pm 1.1^\circ_{sys} \quad (10)$$

$$\phi_{+-} - \phi_{SW} = 0.61^\circ \pm 0.62^\circ_{stat} \pm 1.1^\circ_{sys} \quad (11)$$

The systematic uncertainties include most notably the understanding of the regeneration phase. It should be noted that the extracted ϕ_{+-} has significant correlations with τ_S and Δm . To illustrate the correlation, we show the variation of the central value of ϕ_{+-} in a data subsample:

$$\Delta\phi_{+-} = 229.3[(\Delta m \cdot 10^{-10} \hbar^{-1} s) - 0.52796] \quad (12)$$

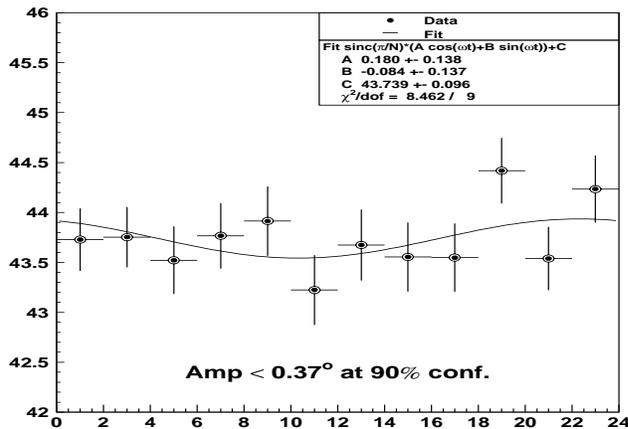


Figure 4: The dependence of ϕ_{+-} on sidereal time.

$$-891.2[(\tau_S \cdot 10^{10} s^{-1}) - 0.89669]$$

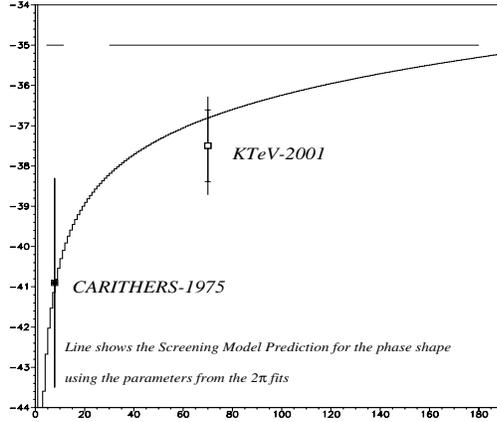
We can now examine the sidereal time dependence of ϕ_{+-} . We perform a fit for only ϕ_{+-} , while fixing Δm and τ_S to values extracted earlier (see Eq. 3.1). This would be logically inconsistent in the context of the traditional framework. However, our goal is to test the standard-model-extension, which predicts no dependence of Δm and τ_S on sidereal time. By similar reasoning, we incur no uncertainty from ϕ_ρ . Thus, the extraction of the sidereal time-dependent amplitudes Δa_1 and Δa_2 has nearly only statistical errors. Figure 4 shows our result. We find a 90% C.L. limit of 0.37 degrees. Using $\cos\chi = 0.6$ and $\gamma = 100$, we limit Δa_1 and Δa_2 to less than $9.2 \cdot 10^{-22}$ GeV at the 90% C.L.

4 Charge Asymmetries

In this section, we present two preliminary results involving the Ke3 charge asymmetry. In the beam that does not strike the regenerator, we would measure δ_L . In the other beam, we use the charge asymmetry to extract valuable information about regeneration. The results are based on approximately 300M and 150M Ke3 events in the vacuum and regenerator beams respectively.

Since the asymmetries are very small, vary from a few % to 0.3%, we combine data from opposite magnet polarity running, which was reversed approximately once per day. This ensures that the oppositely signed charges have identical acceptance in our detector.

One also has to account for the interaction differences between particle and antiparticle in matter (our detector). The most significant of these include an asymmetry in the pion energy deposition in the CsI calorimeter. There is also a potential asymmetry in the pion punchthrough rate to our muon counters, which would veto the event and introduce biases.



$$\begin{aligned} \phi_\rho - \phi_{ana} &= -0.70^\circ \pm 0.88^\circ \pm 0.91^\circ \\ &\quad \text{Stat.} \quad \text{Sys.} \\ \phi_\rho - \phi_{ana} &= -0.70^\circ \pm 1.27^\circ \end{aligned}$$

Figure 5: A comparison of the regeneration phase extracted from the Ke3 charge asymmetry and our theoretical understanding.

4.1 Regeneration Phase

We can measure the regeneration phase directly using the charge asymmetry in the events behind the regenerator. Instead of Eq. 6, the proptime dependence of the charge asymmetry for the regenerated beam is:

$$\delta(\tau) \approx (1 + 2Re x) [2|\rho|e^{-\frac{\Gamma_S - \Gamma_L}{2}\tau} \cos(\Delta m\tau + \phi_\rho) + \delta_L] \quad (13)$$

The largest uncertainty in the analysis involves the understanding of incoherent scatters, which would have a different time dependence and phase. Unlike the 2π final state, the missing neutrino makes it harder to removed scattered background. Likewise, p_K , which is needed to reconstruct τ , is known only up to a two-fold ambiguity. To deal with the momentum reconstruction uncertainty, we rely on our understanding of the detector acceptance. For the scattered background, we rely on a model of their time evolution and phase, and float their normalization in our fit. Figure 5 shows our result for the regeneration phase, as well as the theoretical prediction. The agreement of the two is:

$$\phi_\rho - \phi_{th} = -0.70^\circ \pm 0.88^\circ_{stat} \pm 0.91^\circ_{sys} \quad (14)$$

We also extract $Re\ x$, the real part of the $\Delta S = -\Delta Q$ amplitude. We find a value of:

$$Re\ x = (12 \pm 33 \pm 39) \cdot 10^{-4} \quad (15)$$

4.2 δ_L

For δ_L , we find a value of:

$$\delta_L = 3322 \pm 58\ (stat) \pm 47\ (syst)\ \text{ppm} \quad (16)$$

This is in excellent agreement with previous measurements and 2.4x more precise than the current best result. A combination of all results including ours yields:

$$\delta_L = 3307 \pm 63\ \text{ppm} \quad \chi^2 = 4.2/6\ \text{d.o.f.} \quad (17)$$

The $K\pi 2$ amplitude ratios (η_{+-}, η_{00}) and δ_L can be used to place limits on CPT violation. Using η_{+-} and η_{00} values from¹⁰ and the combined δ_L :

$$\begin{aligned} Re\ (Y + \frac{x - \bar{x}}{2} + a) &= Re(\frac{2}{3}\eta_{+-} + \frac{1}{3}\eta_{00}) - \frac{\delta_L}{2} \\ &= (1650 \pm 16) - (1653 \pm 32) \\ &= -3 \pm 35\ \text{ppm} \end{aligned} \quad (18)$$

where $Re\ a$ parameterizes CPT violation in $K\pi 2$ decays. The result is consistent with no CPT violation and is limited by the charge asymmetry uncertainty. It limits $|Re\ (Y + (x - \bar{x})/2 + a)| < 61\ \text{ppm}$ at the 90% C.L.. Barring fortuitous cancellations, this is thus far the most stringent limit on Y , x , and a .

5 Conclusion

We have presented several new preliminary results on the fundamental kaon parameters. It is based on the entire 1996-97 dataset, which represents 1/2 of all data collected by KTeV. We presented CPT results in the context of the traditional frame work as well as the one advocated by Kostelecky and collaborators. The results are consistent with CPT symmetry.

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