65. *CPT* Invariance Tests in Neutral Kaon Decay

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CPT theorem is based on three assumptions: quantum field theory, locality, and Lorentz invariance, and thus it is a fundamental probe of our basic understanding of particle physics. Strangeness oscillation in $K^0-\overline{K}^0$ system, described by the equation

$$i\frac{d}{dt}\begin{bmatrix}K^0\\ \overline{K}^0\end{bmatrix} = [M - i\Gamma/2]\begin{bmatrix}K^0\\ \overline{K}^0\end{bmatrix} ,$$

where M and Γ are hermitian matrices (see PDG review [1], references [2,3], and KLOE paper [4] for notations and previous literature), allows a very accurate test of CPT symmetry; indeed since CPT requires $M_{11}=M_{22}$ and $\Gamma_{11}=\Gamma_{22}$, the mass and width eigenstates, $K_{S,L}$, have a CPT-violating piece, δ, in addition to the usual CPT-conserving parameter ϵ:

$$K_{S,L} = \frac{1}{\sqrt{2\left(1+|\epsilon_{S,L}|^2\right)}}\left[\left(1+\epsilon_{S,L}\right)K^0 \pm \left(1-\epsilon_{S,L}\right)\overline{K}^0\right]$$

$$\epsilon_{S,L} = \frac{-i\Im\left(M_{12}\right)-\frac{1}{2}\Im\left(\Gamma_{12}\right)\mp\frac{1}{2}\left[M_{11}-M_{22}-\frac{i}{2}\left(\Gamma_{11}-\Gamma_{22}\right)\right]}{m_L-m_S+i(\Gamma_S-\Gamma_L)/2}$$

$$\equiv \epsilon \pm \delta. \tag{65.1}$$

Using the phase convention $\Im(\Gamma_{12})=0$, we determine the phase of ϵ to be $\varphi_{SW}\equiv\arctan\frac{2(m_L-m_S)}{\Gamma_S-\Gamma_L}$. Imposing unitarity to an arbitrary combination of K^0 and $\overline{K}^0$ wave functions, we obtain the Bell-Steinberger relation [5] connecting CP and CPT violation in the mass matrix to CP and CPT violation in the decay; in fact, neglecting $\mathcal{O}(\epsilon)$ corrections to the coefficient of the CPT-violating parameter, δ, we can write [4]

$$\left[\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{\rm SW}\right]\left[\frac{\Re(\epsilon)}{1+|\epsilon|^2}-i\Im(\delta)\right] = \frac{1}{\Gamma_S-\Gamma_L}\sum_f A_L(f)A_S^*(f), \tag{65.2}$$

where $A_{L,S}(f)\equiv A(K_{L,S}\to f)$. We stress that this relation is phase-convention-independent. The advantage of the neutral kaon system is that only a few decay modes give significant contributions to the r.h.s. in Eq. (65.2); in fact, defining for the hadronic modes

$$\alpha_i \equiv \frac{1}{\Gamma_S}\langle\mathcal{A}_L(i)\mathcal{A}_S^*(i)\rangle = \eta_i\ \mathcal{B}(K_S\to i),$$
$$i = \pi^0\pi^0, \pi^+\pi^-(\gamma), 3\pi^0, \pi^0\pi^+\pi^-(\gamma), \tag{65.3}$$

the recent data from CPLEAR, KLOE, KTeV, and NA48 have led to the following determinations (the analysis described in Ref. [4] has been updated by using the recent measurements of K_L

branching ratios from KTeV [6, 7], NA48 [8, 9], the results described in the CP violation in K_L decays minireview, and the KLOE result [10])

$$\begin{aligned}
\alpha_{\pi^+\pi^-} &= ((1.121 \pm 0.010) + i(1.061 \pm 0.010)) \times 10^{-3} \ , \\
\alpha_{\pi^0\pi^0} &= ((0.493 \pm 0.005) + i(0.471 \pm 0.005)) \times 10^{-3} \ , \\
\alpha_{\pi^+\pi^-\pi^0} &= ((0 \pm 2) + i(0 \pm 2)) \times 10^{-6}, \\
|\alpha_{\pi^0\pi^0\pi^0}| &< 1.5 \times 10^{-6} \ \text{ at } 95\% \text{ CL} \ .
\end{aligned} \tag{65.4}$$

The semileptonic contribution to the right-handed side of Eq. (65.2) requires the determination of several observables: we define [2, 3]

$$\begin{aligned}
\mathcal{A}(K^0 \to \pi^- l^+ \nu) &= \mathcal{A}_0(1-y) \ , \\
\mathcal{A}(K^0 \to \pi^+ l^- \nu) &= \mathcal{A}_0^*(1+y^*)(x_+ - x_-)^* \ , \\
\mathcal{A}(\overline{K}^0 \to \pi^+ l^- \nu) &= \mathcal{A}_0^*(1+y^*) \ , \\
\mathcal{A}(\overline{K}^0 \to \pi^- l^+ \nu) &= \mathcal{A}_0(1-y)(x_+ + x_-) \ ,
\end{aligned} \tag{65.5}$$

where x_+ (x_-) describes the violation of the $\Delta S = \Delta Q$ rule in CPT-conserving (violating) decay amplitudes, and y parametrizes CPT violation for $\Delta S = \Delta Q$ transitions. Taking advantage of their tagged $K^0(\overline{K}^0)$ beams, CPLEAR has measured $\Im(x_+)$, $\Re(x_-)$, $\Im(\delta)$, and $\Re(\delta)$ [11]. These determinations have been improved in Ref. [4] by including the information $A_S - A_L = 4[\Re(\delta) + \Re(x_-)]$ (valid at first order in the small parameters), where $A_{L,S}$ are the K_L and K_S semileptonic charge asymmetries, respectively, from the PDG [12] and the new KLOE semileptonic measurement [13]. Here we are also including the T-violating asymmetry measurement from CPLEAR [14] with a finer binning than appearing in the published article.

Table 65.1: Values, errors, and correlation coefficients for $\Re(\delta)$, $\Im(\delta)$, $\Re(x_-)$, $\Im(x_+)$, and $A_S + A_L$ obtained from a combined fit, including KLOE [4, 13] and CPLEAR [14].

	value	Correlations coefficients				
$\Re(\delta)$	$(4.3 \pm 2.7) \times 10^{-4}$	1				
$\Im(\delta)$	$(-0.9 \pm 0.6) \times 10^{-2}$	−0.40	1			
$\Re(x_-)$	$(-0.22 \pm 0.10) \times 10^{-2}$	−0.14	−0.30	1		
$\Im(x_+)$	$(0.06 \pm 0.19) \times 10^{-2}$	−0.12	−0.02	0.34	1	
$A_S + A_L$	$(-0.23 \pm 0.38) \times 10^{-2}$	−0.12	−0.29	0.94	0.18	1

The value $A_S + A_L$ in Table 65.1 can be directely included in the semileptonic contributions to the Bell Steinberger relations in Eq. (65.2)

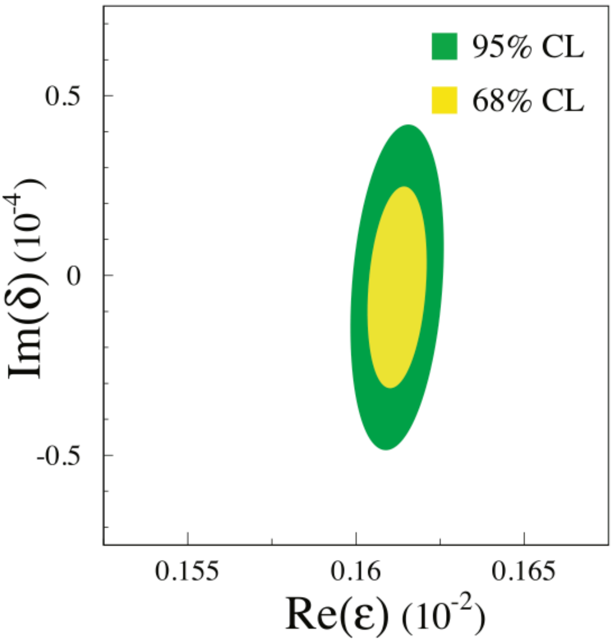
$$\begin{aligned}
&\sum_{\pi\ell\nu} \langle \mathcal{A}_L(\pi\ell\nu)\mathcal{A}_S^*(\pi\ell\nu)\rangle \\
&\quad = 2\Gamma(K_L \to \pi\ell\nu)(\Re(\epsilon) - \Re(y) - i(\Im(x_+) + \Im(\delta))) \\
&\quad = 2\Gamma(K_L \to \pi\ell\nu)((A_S + A_L)/4 - i(\Im(x_+) + \Im(\delta))) \ .
\end{aligned} \tag{65.6}$$

Defining

$$\alpha_{\pi\ell\nu} \equiv \frac{1}{\Gamma_S}\sum_{\pi\ell\nu} \langle \mathcal{A}_L(\pi\ell\nu)\mathcal{A}_S^*(\pi\ell\nu)\rangle + 2i\frac{\tau_{K_S}}{\tau_{K_L}}\mathcal{B}(K_L \to \pi\ell\nu)\Im(\delta) \ , \tag{65.7}$$

we find:

$$\alpha_{\pi\ell\nu} = ((-0.1 \pm 0.2) + i(-0.1 \pm 0.5)) \times 10^{-5} . \quad (65.8)$$



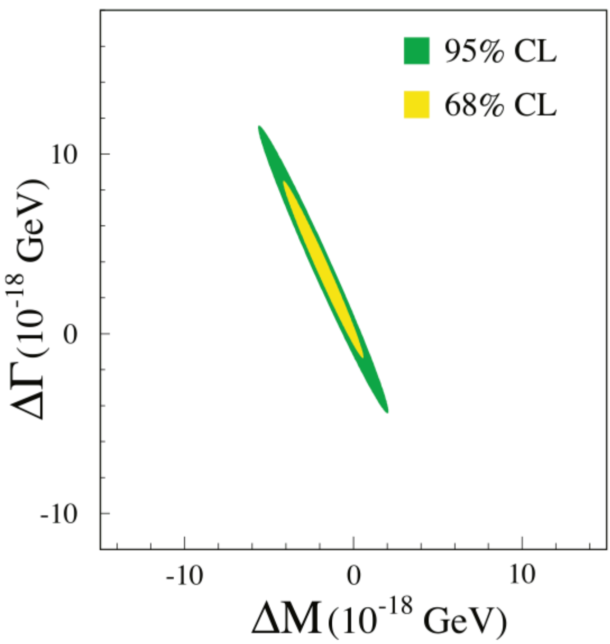


Figure 65.1: Top: allowed region at 68% and 95% C.L. in the $\Re(\epsilon)$, $\Im(\delta)$ plane. Bottom: allowed region at 68% and 95% C.L. in the $\Delta M, \Delta\Gamma$ plane.

Table 65.2: Summary of results: values, errors, and correlation coefficients for $\Re(\epsilon)$, $\Im(\delta)$, $\Re(\delta)$, and $\Re(x_-)$.

	value	Correlations coefficients			
$\Re(\epsilon)$	$(161.2 \pm 0.5) \times 10^{-5}$	+1			
$\Im(\delta)$	$(-0.3 \pm 1.4) \times 10^{-5}$	+0.08	1		
$\Re(\delta)$	$(2.6 \pm 2.5) \times 10^{-4}$	+0.00	−0.05	1	
$\Re(x_-)$	$(-2.7 \pm 1.0) \times 10^{-3}$	+0.05	0.13	−0.30	1

Inserting the values of the α parameters into Eq. (65.2), we find

$$\Re(\epsilon) = (161.2 \pm 0.5) \times 10^{-5},$$
$$\Im(\delta) = (-0.3 \pm 1.4) \times 10^{-5}\,. \qquad (65.9)$$

The complete information on Eq. (65.9) is given in Table 65.2.

Now the agreement with CPT conservation, $\Im(\delta) = \Re(\delta) = \Re(x_-) = 0$, is at 18% C.L.

The allowed region in the $\Re(\epsilon) - \Im(\delta)$ plane at 68% CL and 95% C.L. is shown in the top panel of Fig. 65.1.

The process giving the largest contribution to the size of the allowed region is $K_L \to \pi^+\pi^-$, through the uncertainty on ϕ_{+-}.

The limits on $\Im(\delta)$ and $\Re(\delta)$ can be used to constrain the $K^0 - \overline{K}^0$ mass and width difference

$$\delta = \frac{i(m_{K^0} - m_{\overline{K}^0}) + \frac{1}{2}(\Gamma_{K^0} - \Gamma_{\overline{K}^0})}{\Gamma_S - \Gamma_L} \cos\phi_{SW} e^{i\phi_{SW}} [1 + \mathcal{O}(\epsilon)]\,.$$

The allowed region in the $\Delta M = (m_{K^0} - m_{\overline{K}^0})$, $\Delta\Gamma = (\Gamma_{K^0} - \Gamma_{\overline{K}^0})$ plane is shown in the bottom panel of Fig. 65.1. As a result, we improve on the previous limits (see for instance, P. Bloch in Ref. [12]) and in the limit $\Gamma_{K^0} - \Gamma_{\overline{K}^0} = 0$ we obtain

$$-4.0 \times 10^{-19}\ \mathrm{GeV} < m_{K^0} - m_{\overline{K}^0} < 4.0 \times 10^{-19}\ \mathrm{GeV} \quad \text{at 95 \% C.L.}$$

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