Measurements of CP and T violation parameters in the neutral kaon system at CPLEAR.

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ABSTRACT

The CPLEAR experiment at CERN studies the CP, T and CPT symmetries in the neutral kaon system by measuring the time dependent decay rate asymmetries of initially pure K^0 and $\overline{\mathrm{K}}^0$ states. Results on η_{+-}, η_{+-0}, Δm and x are reported, as well as on the first direct test of T violation and CPT invariance in K^0-$\overline{\mathrm{K}}^0$ oscillations. Our results are consistent with CPT invariance and allow for an improved limit on the K^0-$\overline{\mathrm{K}}^0$ mass difference.

1 Introduction

The CPLEAR experiment[1] investigates CP, T and CPT symmetries in the neutral kaon system. Contrary to the traditional experiments, CPLEAR uses initially pure K^0 and $\overline{\mathrm{K}}^0$ and measures the difference between the rates of their decays to a variety of final states, $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi e\nu$ and $\pi^+\pi^-\pi^0$. The CP, T and CPT violation parameters can be extracted from the time dependent decay rate asymmetries:

$$A_f(t) \equiv \frac{R_{\overline{\mathrm{K}}^0\to\overline{\mathrm{f}}}(t) - R_{\mathrm{K}^0\to\mathrm{f}}(t)}{R_{\overline{\mathrm{K}}^0\to\overline{\mathrm{f}}}(t) + R_{\mathrm{K}^0\to\mathrm{f}}(t)}$$

The use of such asymmetries has the advantage of cancelling many systematic effects related to the detector acceptance. CPLEAR measures the CP violation parameters η_{+-} for $\pi^+\pi^-$ and η_{+-0} for $\pi^+\pi^-\pi^0$, Δm, the $\mathrm{K_L}$-$\mathrm{K_S}$ mass difference, and the parameter x (to test the validity of the $\Delta S = \Delta Q$ rule). A direct measurement of T violation is possible for the first time, as well as a direct test of CPT invariance. An indirect test of CPT invariance is made by comparing φ_{+-}, the phase of η_{+-}, to φ_{sw}, the superweak phase. The precision of the CPLEAR measurements is either better than, or comparable to, the precision of the world average values.

2 Experimental Setup

The K^0 and $\overline{\mathrm{K}}^0$ mesons are produced in equal amounts in $\overline{\mathrm{p}}\mathrm{p}$ annihilations at rest, through the channels:

$$\overline{\mathrm{p}}\mathrm{p} \to \mathrm{K}^-\pi^+\mathrm{K}^0$$

$$\overline{\mathrm{p}}\mathrm{p} \to \mathrm{K}^+\pi^-\overline{\mathrm{K}}^0$$

each one with a branching ratio of $\approx 2 \cdot 10^{-3}$. The strangeness of the neutral kaon $\mathrm{K}^0(\overline{\mathrm{K}}^0)$ at t=0 is defined by the companion charged kaon $\mathrm{K}^-(\mathrm{K}^+)$.

The CPLEAR detector[2] is shown in Fig. 1. The detector has a cylindrical geometry and is mounted in-

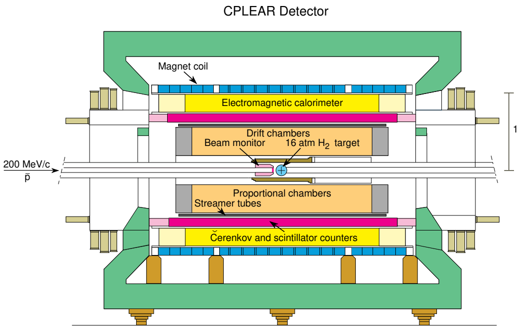

Figure 1: The CPLEAR detector.

side a solenoid magnet of 3.6 m length and 1 m radius, producing a field of 0.44 T. It allows the detection of neutral kaon decays for the eigentime range $0 \leq \tau \leq 20\tau_S$ (τ_S is the $\mathrm{K_S}$ mean life). The 200 Mev/c antiprotons from the Low Energy Antiproton Ring (LEAR) of CERN at a rate $\approx 10^6 s^{-1}$ stop and annihilate inside a gaseous hydrogen target (16 bar pressure) at the center of the detector. Viewed from the target to the outside, the detector consists of two multiwire proportional chambers and six drift chambers which are the tracking devices, two layers of streamer tubes giving a fast information of the z coordinate for each track, a scintillator-Cerenkov-scintillator sandwich (PID) which provides identification of charged kaons, pions and electrons, and an electromagnetic calorimeter to detect photons. Special care was taken in the design and construction of the detector to minimize the material in the decay volume and hence the effects due to regeneration of the neutral kaons.

3 Trigger and offline event selection.

A multi-level trigger system, including custom-made hardwired processors, provides a fast background rejection. The trigger is based on particle identification, kinematical selection and shower counting, and provides a rejection factor of ≈ 1000.

For the offline selection of the decays to $\pi^+\pi^-$, $\pi e\nu$, and $\pi^+\pi^-\pi^o$ we use kinematically and geometrically constrained fits, and electron identification. The results from the analysis of data taken between 1990 and mid 1994 are presented here.

4 $\mathrm{K^o}(\overline{\mathrm{K^o}}) \to \pi^+\pi^-$ decay mode.

CP violation in the $\pi^+\pi^-$ decay mode (CP=+1) of neutral kaons manifests itself in the occurence of $\mathrm{K_L} \to \pi^+\pi^-$ decays and is commonly described by the parameter η_{+-}. The asymmetry

$$A_{+-}(t) \equiv \frac{R_{\overline{\mathrm{K^o}}\to\pi^+\pi^-}(t) - \alpha R_{\mathrm{K^o}\to\pi^+\pi^-}(t)}{R_{\overline{\mathrm{K^o}}\to\pi^+\pi^-}(t) + \alpha R_{\mathrm{K^o}\to\pi^+\pi^-}(t)} =$$

$$= -2\frac{|\eta_{+-}|e^{1/2(\gamma_S-\gamma_L)t}cos(\Delta m - \varphi_{+-})}{1+|\eta_{+-}|^2 e^{(\gamma_S-\gamma_L)t}}$$

where $\gamma_{S,L}$ are the $K_{S,L}$ decay widths, and α is a normalization factor, is well suited to extract both the magnitude $|\eta_{+-}|$ and the phase φ_{+-} of η_{+-}. A total of 16 million events has been selected in the decay-time region 0-20 τ_S. Figure 2 shows separately the decay rates of $\mathrm{K^o}$ and $\overline{\mathrm{K^o}}$ after acceptance correction and background substraction and well demonstrates the expected CP violation.

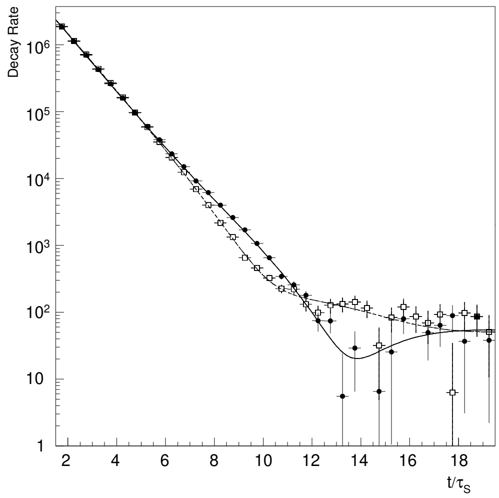

Figure 2: Decay rates of $\mathrm{K^o}$ ($\bullet$) and $\overline{\mathrm{K^o}}$ ($\circ$).

Figure 3 shows the asymmetry $A_{+-}(t)$. The data entering $A_{+-}(t)$ are corrected, on an event by event basis, for the momentum dependence of the tagging efficiency of $\mathrm{K^o}$ relative to $\overline{\mathrm{K^o}}$ (determined at short decay-times) and for regeneration effects. The $\mathrm{K^o}$ and $\overline{\mathrm{K^o}}$ tagging efficiencies are not equal due to the different interactions of $\mathrm{K^+}$ and $\mathrm{K^-}$, and of π^+ and π^-, in the detector material. A fit to $A_{+-}(t)$ gives the values of $|\eta_{+-}|$, φ_{+-} and α.

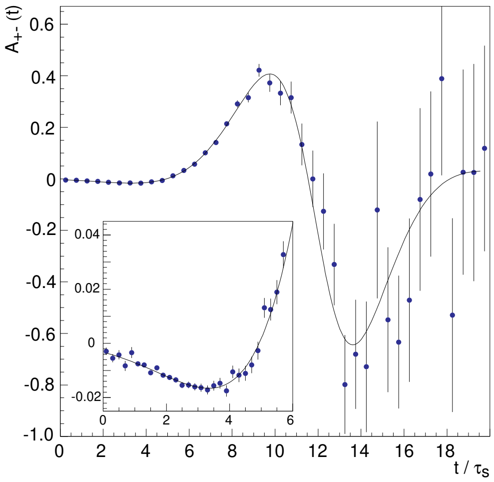

Figure 3: The asymmetry A_{+-} vs the decay time. The solid line represents the result of the fit.

The results of the fit, using the CPLEAR Δm

value (see next section), are[3]:

$$|\eta_{+-}| = (2.312 \pm 0.043_{stat} \pm 0.030_{stat} \pm 0.011_{\tau_S}) \times 10^{-3}$$

$$\varphi_{+-} = 42.7^\circ \pm 0.9^\circ_{stat} \pm 0.6^\circ_{syst} \pm 0.9^\circ_{\Delta m}$$

The external error on $|\eta_{+-}|$ is dominated by the uncertainty on the value of τ_S ($0.08926 \pm 0.00012\, ns$)[4], while that on φ_{+-} by the uncertainty on Δm. The systematic error on φ_{+-} is almost entirely due to the uncertainty in the coherent regeneration correction. In the absence of experimental data for the difference between the forward scattering amplitudes of K° and $\overline{\mathrm{K}}$° in the momentum region of the present experiment (<800 MeV/c), we have used the values calculated recently by Eberhard and Uchiyama[5]. In 1996 a dedicated measurement of the difference of the K° $-$ $\overline{\mathrm{K}}$° forward scattering amplitudes in carbon at low momentum will be done with the CPLEAR detector[6]. After this measurement the systematic error on φ_{+-} due to regeneration effects is expected to decrease by a factor ≥ 2. Figure 4 shows our result on φ_{+-} in comparison with previous measurements[4,7] for the same Δm value[4], and the CPLEAR '92 result[8]. We estimate that at the end of 1996 the total error on our measurement will be 0.7°.

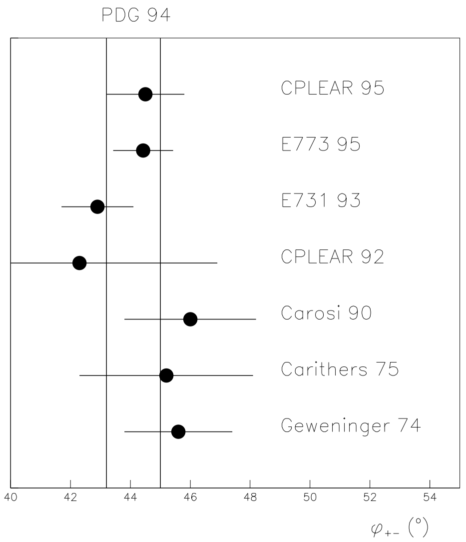

Figure 4: φ_{+-} values from CPLEAR[3,8] and other experiments[4,7]. The two vertical lines correspond to the PDG '94 value $\pm 1\sigma$.

5 K°($\overline{\mathrm{K}}$°) $\rightarrow \pi e \nu$ decay mode.

In the semileptonic channel the following four independent decay rates can be measured:

$$R^+(t) = R(\mathrm{K}^\circ \rightarrow \pi^- e^+ \nu)$$

$$R^-(t) = R(\mathrm{K}^\circ \rightarrow \pi^+ e^- \overline{\nu})$$

$$\overline{R}^+(t) = R(\overline{\mathrm{K}}^\circ \rightarrow \pi^- e^+ \nu)$$

$$\overline{R}^-(t) = R(\overline{\mathrm{K}}^\circ \rightarrow \pi^+ e^- \overline{\nu})$$

Assuming the validity of the $\Delta S = \Delta Q$ rule the neutral kaon strangeness at the decay time is tagged through the lepton charge, and the above four rates can be interpreted as measuring the following time-dependent transition rates:

$$R^+(t) = R(\mathrm{K}^\circ{}_{t=0} \rightarrow \mathrm{K}^\circ(t))$$

$$R^-(t) = R(\mathrm{K}^\circ{}_{t=0} \rightarrow \overline{\mathrm{K}}^\circ(t))$$

$$\overline{R}^+(t) = R(\overline{\mathrm{K}}^\circ{}_{t=0} \rightarrow \mathrm{K}^\circ(t))$$

$$\overline{R}^-(t) = R(\overline{\mathrm{K}}^\circ{}_{t=0} \rightarrow \overline{\mathrm{K}}^\circ(t))$$

From these rates we can construct several asymmetries which are sensitive to different parameters of the kaon mixing matrix (Δm, ϵ_T and δ_{CPT}). The total number of events selected in the semileptonic channel is 7×10^5. But for Δm, all the results presented here are preliminary.

The asymmetry

$$A_{\Delta m}(t) \equiv \frac{\overline{R}^-(t) + R^+(t) - \overline{R}^+(t) - R^-(t)}{\overline{R}^-(t) + R^+(t) + \overline{R}^+(t) + R^-(t)} =$$

$$= \frac{e^{-1/2(\gamma_S + \gamma_L)t} cos(\Delta m t)}{(1 + Re(x))e^{-\gamma_S t} + (1 - Re(x))e^{-\gamma_L t}}$$

is sensitive to Δm and $Re(x)$. From a fit to the asymmetry $A_{\Delta m}$ [Fig. 5] we obtain[9]:

$$\Delta m = (0.5274 \pm 0.0029_{stat} \pm 0.0005_{syst}) \times 10^{10} \hbar s^{-1}$$

and

$$Re(x) = (12.4 \pm 11.9_{stat} \pm 6.9_{syst}) \times 10^{-3}$$

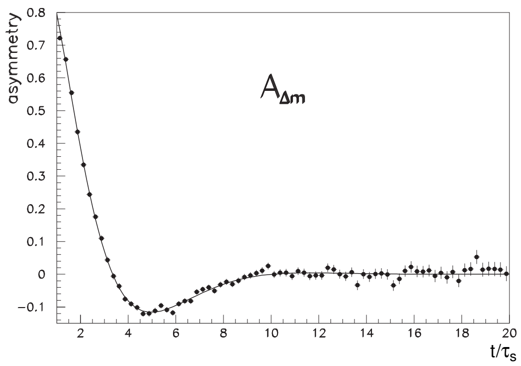

Figure 5: The asymmetry $A_{\Delta m}$ vs the decay time. The solid line represents the result of the fit.

The systematic errors on both these quantities are dominated by the uncertainty in the background level, mostly from $\pi^+\pi^-$ decays. Figure 6 shows the

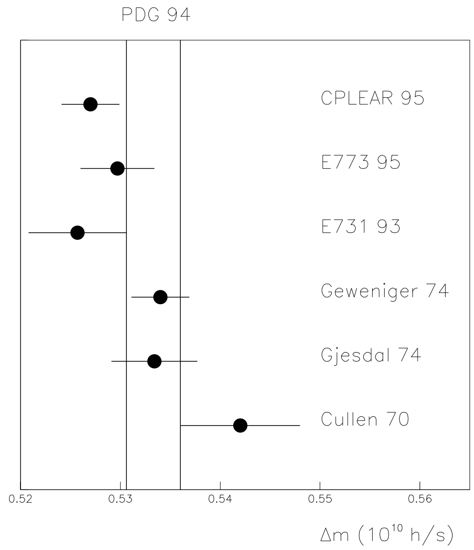

Figure 6: Δm values from CPLEAR[9] and other experiments[4,7]. The two vertical lines correspond to the PDG '94 value $\pm 1\sigma$.

comparison of our Δm value with the results of other experiments[4].

Figure 7 shows the asymmetry

$$A_T(t) \equiv \frac{\overline{R}^+(t) - R^-(t)}{\overline{R}^+(t) + R^-(t)}$$

which is a direct measurement of T violation. A fit to this asymmetry gives:

$$A_T = (6.3 \pm 2.1_{stat} \pm 1.8_{syst}) \times 10^{-3}$$

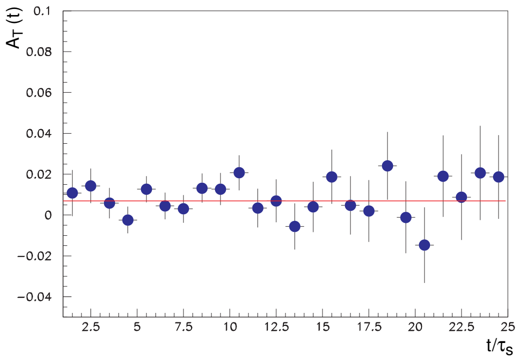

Figure 7: The asymmetry $A_T(t)$ vs the decay time. The line represents the result of the fit.

The asymmetry

$$A_{CPT}(t) \equiv \frac{\overline{R}^-(t) - R^+(t)}{\overline{R}^-(t) + R^+(t)}$$

($A_{CPT} \Rightarrow 4Re(\delta_{CPT})$ for $t \gg \tau_S$ and $x = 0$) provides a direct test of CPT invariance. A fit to A_{CPT} gives for $Re(\delta_{CPT})$ a value compatible with zero,

$$Re(\delta_{CPT}) = (0.07 \pm 0.53_{stat} \pm 0.45_{syst}) \times 10^{-3}$$

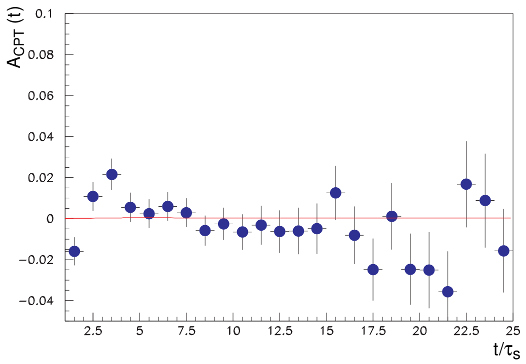

Figure 8: The asymmetry $A_{CPT}(t)$ vs the decay time. The line represents the result of the fit.

The asymmetry $A_2(t)$ shown in Fig. 9,

$$A_2(t) \equiv \frac{\overline{R}^-(t) + \overline{R}^+(t) - R^-(t) - R^+(t)}{\overline{R}^-(t) + \overline{R}^+(t) + R^-(t) + R^+(t)} \simeq$$

$$2Re(\epsilon_T) + 4e^{-\gamma t} \frac{Im(x)sin(\Delta m t) - Re(\epsilon_T)cos(\Delta m t)}{e^{-\gamma_S t} + e^{-\gamma_L t}}$$

where $\gamma = (\gamma_S + \gamma_L)/2$, $Re(x) = 0$ and $\delta_{CPT} = 0$, is sensitive to $Im(x)$. The fit yields:

$$Im(x) = (4.8 \pm 4.3_{stat} \pm 0.6_{syst}) \times 10^{-3}$$

This value has to be compared with the world average value which is $Im(x) = (-3 \pm 26) \times 10^{-3}$[4].

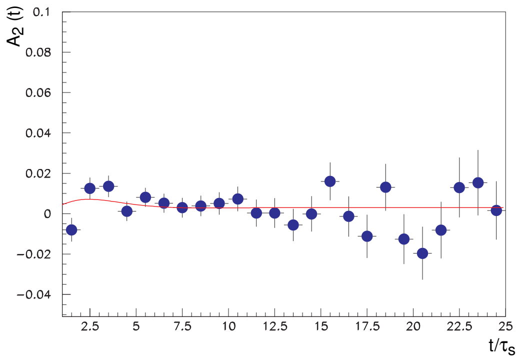

Figure 9: The asymmetry $A_2(t)$ vs the decay time. The line represents the result of the fit.

6 $K^\circ(\overline{K}^\circ) \to \pi^+\pi^-\pi^\circ$ decay mode.

The CP-parity of the final state $\pi^+\pi^-\pi^\circ$ is $(-1)^{l+1}$, where l is the relative orbital angular momentum of the $\pi^+\pi^-$ pair with respect to the π°. So the $\pi^+\pi^-\pi^\circ$ state may have even or odd CP-parity depending on the value of l. The decay $K_L \to \pi^+\pi^-\pi^\circ$ is CP-allowed when the final state is the kinematically preferred $l = 0$ state, while the decay $K_S \to \pi^+\pi^-\pi^\circ$ is a mixture of CP-violating, $l = 0$, and CP-conserving, but kinematically suppressed, $l = 1$ transitions. Under exchange of the π^+ and π^- in the K° rest frame the $l = 1$ state is antisymmetric and hence if the decay rates are integrated over all pion configurations, the CP-allowed K_S contribution cancels in the $K_S K_L$ interference. The time dependent asymmetry,

$$A_{+-0}(t) \equiv \frac{R_{\overline{K}^\circ\to\pi^+\pi^-\pi^\circ}(t) - R_{K^\circ\to\pi^+\pi^-\pi^\circ}(t)}{R_{\overline{K}^\circ\to\pi^+\pi^-\pi^\circ}(t) + R_{K^\circ\to\pi^+\pi^-\pi^\circ}(t)} =$$

$$\simeq 2Re(\epsilon_T + \delta_{CPT}) - 2e^{-1/2(\gamma_S-\gamma_L)t}[Re(\eta_{+-0})cos(\Delta m t)$$

$$-Im(\eta_{+-0})sin(\Delta m t)]$$

is shown in Fig. 10. The total number of events is 1.5×10^5. From a fit to this asymmetry we obtain as preliminary result:

$$Re(\eta_{+-0}) = (-4 \pm 17_{stat} \pm 3_{syst}) \times 10^{-3}$$

$$Im(\eta_{+-0}) = (-16 \pm 20_{stat} \pm 8_{syst}) \times 10^{-3}$$

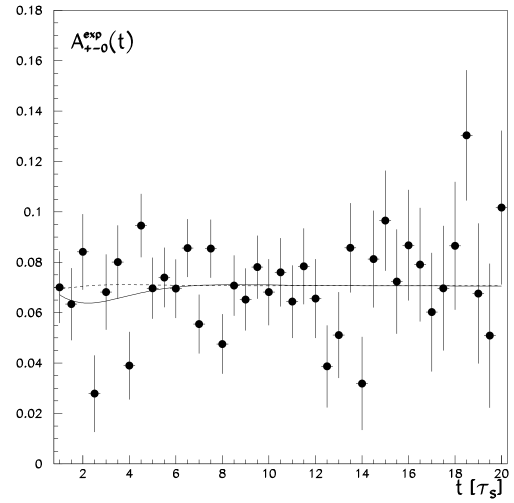

Figure 10: The asymmetry $A_{+-0}(t)$ vs the decay time. The solid (dotted) line represents the result of the fit when we float $Re(\eta_{+-0})$ and $Im(\eta_{+-0})$ (only $Im(\eta_{+-0})$ with the constraint $Re(\eta_{+-0}) = Re(\eta_{+-})$).

The value of $Re(\eta_{+-0})$ is consistent with been equal to $Re(\eta_{+-})$. We note here that in the hypothesis of CPT conservation, any deviation of η_{+-0} from η_{+-} would be due to direct CP violation which contributes only to $Im(\eta_{+-0})$. Figure 11 shows our result, in comparison with the results from other experiments.

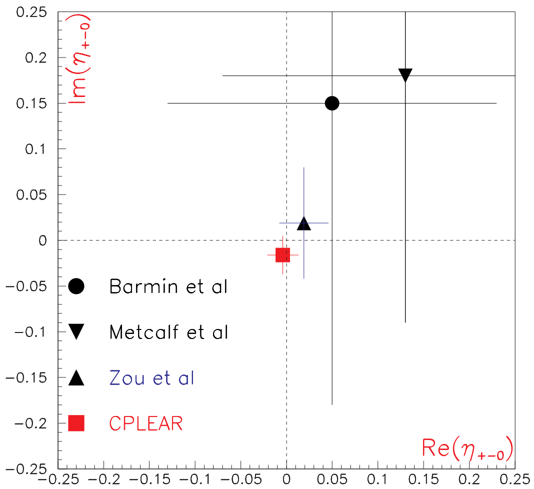

Figure 11: $Im(\eta_{+-0})$ vs $Re(\eta_{+-0})$ for CPLEAR (preliminary) and other experiments[4,10].

7 Indirect CPT test.

The best limit on CPT violation is obtained by comparing the phase of η_{+-} with the superweak angle $\varphi_{sw} = tan^{-1}(\frac{2\Delta m}{\Delta\Gamma})$, where $\Delta\Gamma = \gamma_S - \gamma_L$. Note that if we take the available data[4] the phase difference between φ_{+-} and φ_{sw} can be as large as $3°$[11] even in the absence of CPT violation. The equation that relates η_{+-} and ϵ_T is:

$$\eta_{+-} = \epsilon_T + \delta_\perp + i\varphi_0 + \epsilon'$$

where ϵ_T has a phase φ_{sw} and $\delta_\perp$ describes the CPT violation parameter perpendicular to ϵ_T,

$$-\delta_\perp \equiv \frac{i\Delta\Gamma - 2\Delta m}{4\Delta m^2 + \Delta\Gamma^2}(M_{22} - M_{11} + \frac{\Delta m}{\Delta\Gamma}(\Gamma_{22} - \Gamma_{11}))$$

where $M_{ij} - \frac{1}{2}\Gamma_{ij}$ are the elements of the kaon mixing matrix. The term φ_0 is derived to be:

$$\varphi_0 = \frac{\gamma_L}{\gamma_S}[2BR(K_L \to \pi l\nu)Im(x)$$

$$+BR(K_L \to 3\pi)Im(\eta_{3\pi} - \eta_{+-})]$$

The term ϵ' describes the CP violation in the decay amplitude and can be neglected since $|\epsilon'| < 10^{-5}$[12]. Figure 12 shows the relation between the CP violating parameters η_{+-}, ϵ_T, $\delta_\perp$, φ_0 and ϵ'.

Using our improved limits for $Im(\eta_{+-0})$ and $Im(x)$, our measurements of φ_{+-} and Δm, and $\Delta\Gamma$ from[4], we find:

$$|\delta_\perp| < 10^{-4}(90\%C.L.)$$

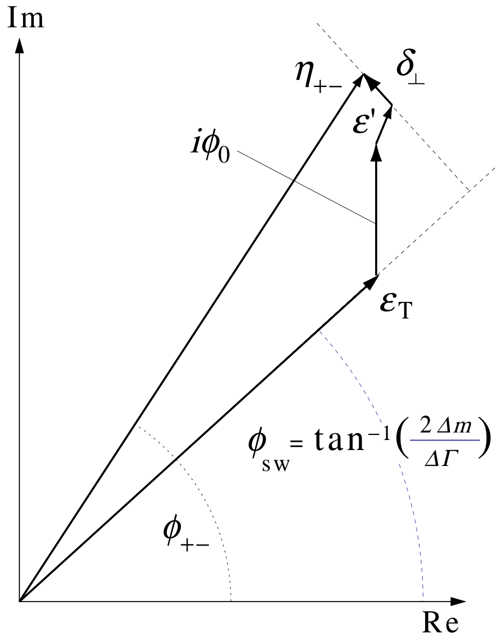

Figure 12: The relation between the CP violating parameters η_{+-}, ϵ_T, $\delta_\perp$, φ_0 and ϵ'.

Assuming CPT conservation in the decay amplitude, we obtain:

$$|\frac{M_{\overline{\mathrm{K}}^\circ} - M_{\mathrm{K}^\circ}}{M_K}| < 2.0 \cdot 10^{-18}$$

This is the best limit on a particle-antiparticle mass difference.

8 Summary

CPLEAR provides information on the CP, T and CPT violation parameters. The parameters φ_{+-} and Δm are measured in an independent way, with a precision comparable to the one of the best published results. Improved values for η_{+-0} as well as for $Re(x)$ and $Im(x)$ are determined. CPLEAR provides also the first direct measurement of T violation through a comparison of K°, $\overline{\mathrm{K}}^\circ$ decay rates, and a direct test of CPT invariance. Finally taking into account all our results we can perform one of the best indirect tests of CPT invariance. The full analysis of the data (including the data to be collected up to 1995) will decrease our statistical errors by a factor ≥ 2. A dedicated measurement of the regeneration parameters in 1996 will help to decrease our systematic error in φ_{+-} by more than a factor of 2.

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