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 acceptances. CPLEAR measures the CP violation parameters η_{+-} for $\pi^+\pi^-$ and η_{+-0}

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for $\pi^+\pi^-\pi^\circ$, Δm, the K_L-K_S mass difference, and the parameter x (to test the validity of the $\Delta S = \Delta Q$ rule) from the semileptonic decays. The possibility of measuring the strangeness of the neutral kaon at its production and at its decay is a superior tool for directly measure T violation, as well as for directly testing CPT invariance. Moreover such a tool potentially allows the study of discrete symmetries in various parameters and form factors of the semileptonic decays as presented by Lee and Wu [14]. An indirect test of CPT invariance is made by comparing φ_{+-}, the phase of η_{+-}, to φ_{sw}, the superweak phase. First results have been obtained, including data up to middle '94, for the time dependent asymmetries in the $\pi^+\pi^-$, the semileptonic and 3π channels, from which the CP, T and CPT parameters have been evaluated with statistical significance better than of many existing measurements. In some cases the results are unique.

2 Experimental Setup

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

$$\overline{p}p \longrightarrow K^-\pi^+K^\circ$$

$$\overline{p}p \longrightarrow K^+\pi^-\overline{K}^\circ$$

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

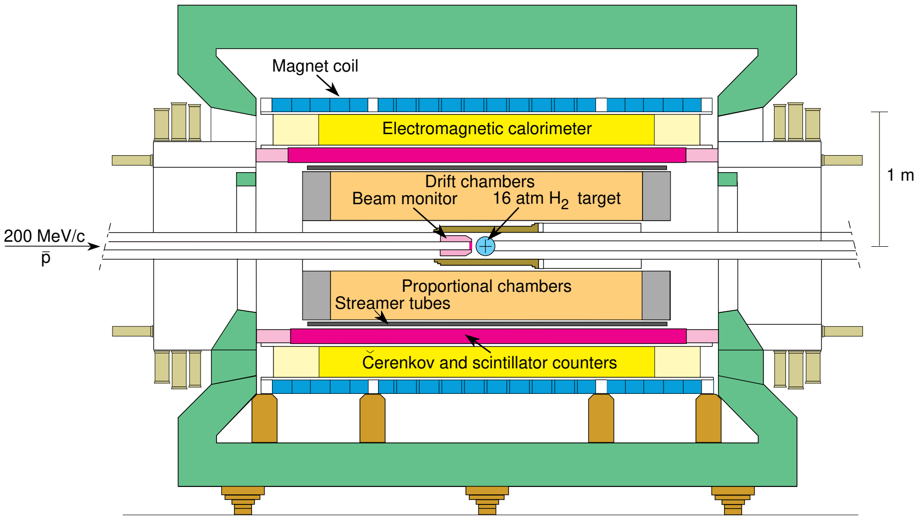

Figure 1: The CPLEAR detector.

The CPLEAR detector [2] is shown in Fig. 1. The detector has a cylindrical geometry and is mounted inside 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 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(S1)-Cerenkov(CE)-scintillator(S2) sandwich (PID) which provides identification of charged kaons, pions and electrons, and an electromagnetic calorimeter to detect photons. The electromagnetic showers are detected in the lead/gas sampling calorimeter using 17280 tubes, each with one wire, working in a limited streamer mode. It consists of three segments, each of 120°, and of 18 layers in depth. Each layer of tubes is sandwiched between two layers of pick-up strips (±30° with respect to the tubes). 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 and absorption of the neutral kaons.

A multi-level trigger system, including custom-made hardwired processors, provides a fast event selection. The trigger is based on particle identification, kinematical selection and shower counting, and provides a rejection factor of ≈ 1000 in less than $5\mu s$.

3 Detemination of Δm and x from $\mathrm{K}^\circ(\overline{\mathrm{K}}^\circ) \rightarrow \pi e \nu$ decays.

The CPLEAR experiment has the capacity to determine the strangeness of the neutral kaons both at their production and at their decays. Therefore is able to measure the four decay rates R, as a function of the decay eigentime τ of the kaon, depending on the strangeness of the neutral kaon (K^0or $\overline{\mathrm{K}}^0$) at the production time, $\tau = 0$, and on the charge of the decay lepton (e^+or e^-):

$$R^+(\tau) \equiv R[\mathrm{K}^0{}_{(\tau=0)} \rightarrow \mathrm{e}^+\pi^-\nu](\tau) \qquad \overline{R}^-(\tau) \equiv R[\overline{\mathrm{K}}^0{}_{(\tau=0)} \rightarrow \mathrm{e}^-\pi^+\overline{\nu}](\tau) \tag{1}$$

$$R^-(\tau) \equiv R[\mathrm{K}^0{}_{(\tau=0)} \rightarrow \mathrm{e}^-\pi^+\overline{\nu}](\tau) \qquad \overline{R}^+(\tau) \equiv R[\overline{\mathrm{K}}^0{}_{(\tau=0)} \rightarrow \mathrm{e}^+\pi^-\nu](\tau) \tag{2}$$

The $\mathrm{K_L} - \mathrm{K_S}$ mass difference Δm is obtained from the asymmetry

$$\begin{aligned} A_{\Delta m}(\tau) &= \frac{[R^+(\tau) + \overline{R}^-(\tau)] - [\overline{R}^+(\tau) + R^-(\tau)]}{[R^+(\tau) + \overline{R}^-(\tau)] + [\overline{R}^+(\tau) + R^-(\tau)]} = \\ &= \frac{2\cos(\Delta m \tau) e^{-\frac{1}{2}(\tau/\tau_\mathrm{L} + \tau/\tau_\mathrm{S})}}{(1 + 2\mathrm{Re}(x))e^{-\tau/\tau_\mathrm{S}} + (1 - 2\mathrm{Re}(x))e^{-\tau/\tau_\mathrm{L}}}\ , \end{aligned} \tag{3}$$

where a possible violation of the $\Delta S = \Delta Q$ rule is taken into account by the parameter $\mathrm{Re}(x)$ [4], and τ_S (τ_L) denotes the mean life of $\mathrm{K_S}$ ($\mathrm{K_L}$).

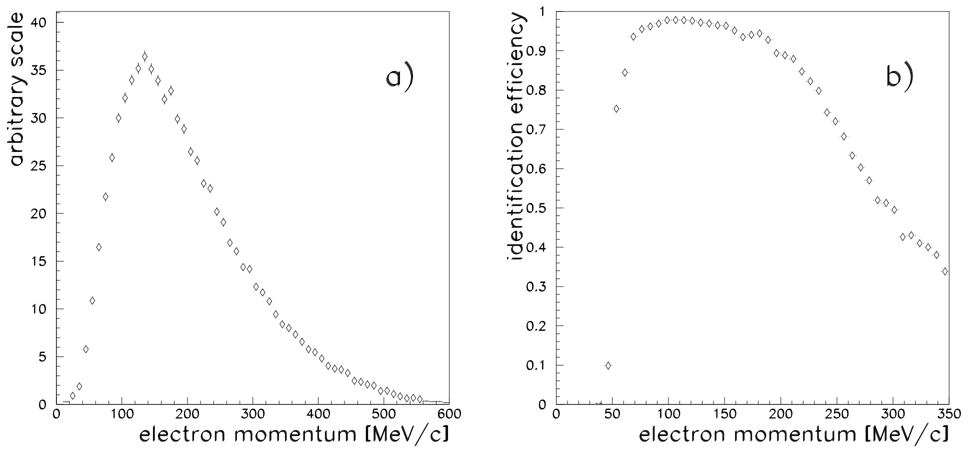

Figure 2: a) Expected electron momentum spectrum in semileptonic decays of neutral kaons. b) Electron identification efficiency versus momentum when 2% of pions fake electrons.

The effect of the strangeness normalisation and the semileptonic channel identification is particularly small due to the manner of construction of the asymmetry $A_{\Delta m}$ (Eq. 3) which compares two sets of data containing both $\mathrm{K}^0$and $\overline{\mathrm{K}}^0$and also $\mathrm{e}^+$and e^-. Similarly, the rates entering $A_{\Delta m}$ do not need to be corrected for regeneration in the detector material, since in the construction of $A_{\Delta m}$ all terms linear in the regeneration amplitude cancel.

A first selection requires four tracks with zero total charge, good track quality and at least one charged kaon candidate. The annihilation vertex (primary vertex) must lie within the beam stopping distribution and a separate vertex for the decay of the neutral kaon (secondary vertex) is required. A cut on the minimum distance between the two vertices (1 cm in the transverse plane) is applied to remove ambiguities on the track assignment to either vertex, and to reduce the background from other $\overline{\rm p}$p annihilation channels to less than 1% for decay times greater than 1 τ_S. A kinematical fit requiring the K^0 missing mass at the primary vertex is performed to validate the hypothesis of the $(K^{\pm}\pi^{\mp}K^0)$ channel.

The semileptonic decay channel is selected by identifying one of the secondary tracks as an electron or a positron. Electron-pion separation is based on the energy loss in S1 and S2, the number of photo-electrons per unit path length in CE and the time of flight of the particle from the decay vertex to S1. The selection has been optimized using electron data from converted photons and pions from decays of neutral kaons into $\pi^+\pi^-$. The expected electron momentum spectrum obtained from Monte Carlo is shown in Fig. 2 a). The electron identification efficiency versus momentum is shown in Fig. 2 b). This efficiency is obtained requiring that less than 2% of pions are misidentified as electrons, independently of the momentum. Under these conditions, muons have an average probability of $\approx$ 15% to be misidentified as electrons. A constrained fit requiring energy-momentum conservation under the assumption of a missing neutrino and the alignment of the K^0 momentum vector with the line joining the two vertices is performed. This fit also improves the resolution of the decay time and fixes the absolute time scale of the neutral kaon with a precision better than 2×10^{-4}. Simulation studies show that the decay time resolution varies from 5 ps to 15 ps as a function of the neutral kaon decay radius. Finally, events which fit to the $(K\pi K^0,\ K^0\rightarrow\pi^+\pi^-)$ hypothesis with high probability are removed in order to reduce the $\pi^+\pi^-$background which is dominant at short decay times. The final sample contains $\approx 700,000$ $(K^0,\ \overline{K}^0\rightarrow\pi e\nu)$ events collected up to mid 1994.

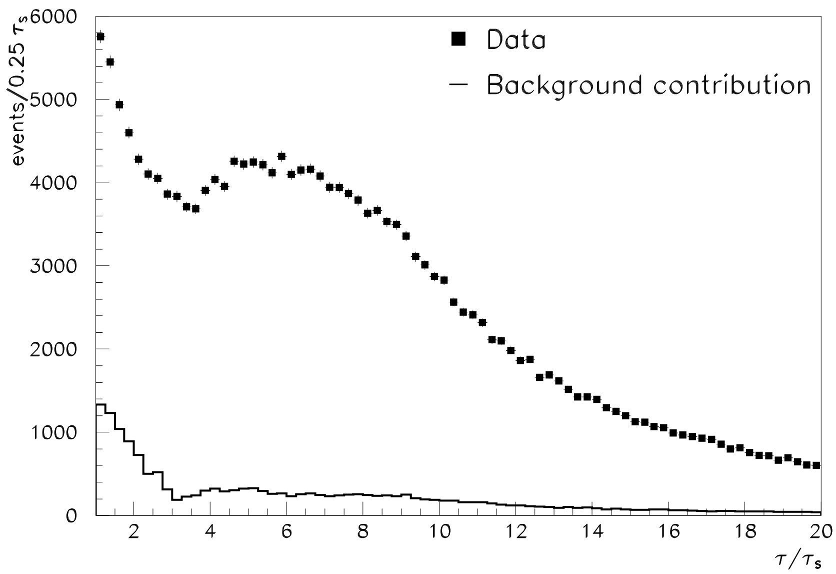

Figure 3: Decay time distribution for real data (squares) and expected background contribution obtained from simulation (solid line).

Due to the different strong interaction cross-sections of K^+ and K^-, as well as of π^+ and π^-, the detection efficiencies of a $(K^+\pi^-)$ pair and a $(K^-\pi^+)$ pair are not identical. The difference of the overall $(K^+\pi^-)$ and $(K^-\pi^+)$ efficiencies is of the order of 15%. To restore the initial K^0-$\overline{K}^0$ production symmetry, we have to correct for this difference in the tagging efficiencies. Let ξ denote the ratio of the two efficiencies, $\xi = \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$, which depends on the momenta of the primary pion and kaon $[\xi(\vec{p}_K,\vec{p}_\pi)]$. This ratio is independent of the decay mode and is determined from the decay rates of neutral kaons into $\pi^+\pi^-$. The weight ξ is then applied event by event to the semileptonic data. The error on Δm due to the uncertainty of this procedure is smaller than $0.00002 \times 10^{10}\hbar/\mathrm{s}$.

We have also studied the difference in the detection efficiencies of the two possible final states ($\pi^+ e^- \overline{\nu}$) and ($\pi^- e^+ \nu$). Using data from photon conversions, we have not observed any difference in the detection of $e^+$and e^-. On the other hand, the difference between the $\pi^+$and π^-cross-sections with matter leads to the detection of a small excess of π^+. We define the parameter η as the ratio of the two detection efficiencies $\epsilon(\pi^+)$ and $\epsilon(\pi^-)$. This ratio is measured as a function of the transverse and longitudinal momentum of the pion by selecting kinematically, in minimum bias events, the annihilation pionic channel and applying subsequently all the online and offline pion selection criteria. We find that η never deviates from unity by more than 2.5%, inducing, at the present stage of the analysis, an uncertainty on Δm of $0.0001 \times 10^{10}\hbar/\mathrm{s}$.

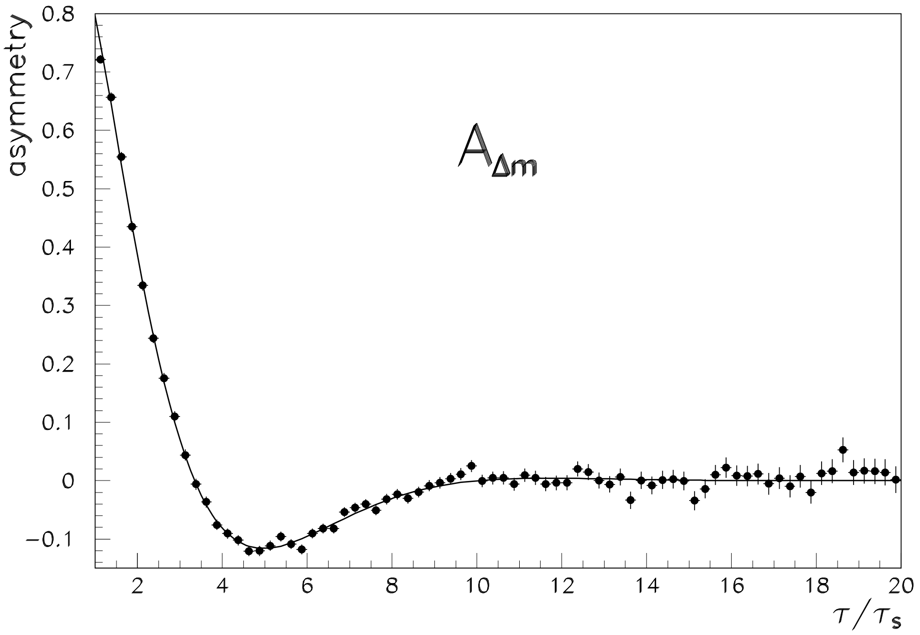

Figure 4: The asymmetry $A_{\Delta m}$ versus the decay time (in unit of τ_S). The solid line represents the result of the fit.

The signal consists of correctly reconstructed $\pi e \nu$ events and of $\pi \mu \nu$ events seen as $\pi e \nu$ ($\approx$ 10% of the signal). The background is determined from a Monte Carlo simulation. The main background source consists of residual neutral kaon decays to $\pi^+\pi^-$and is concentrated at short decay times. At large decay times there are contributions from $\pi^+\pi^-\pi^0$ decays and from $\pi l \nu$ decays where the pion and the lepton assignments are exchanged. In the simulation, each channel is scaled to the same number of generated $\overline{\mathrm{p}}\mathrm{p}$ annihilations. The sum of the background contributions normalized by the weight ξ as the signal (since both the signal and the background result from neutral kaon decays) is displayed in Fig. 3 by the solid line. The background causes a dilution in the asymmetry $A_{\Delta m}$ of Eq. 3, which is accounted for by the factor $f_b(\tau)$:

$$f_b(\tau) = \frac{1 + \frac{B^+(\tau)+\overline{B}^-(\tau)-B^-(\tau)-\overline{B}^+(\tau)}{R^+(\tau)+\overline{R}^-(\tau)-R^-(\tau)-\overline{R}^+(\tau)}}{1 + \frac{B^+(\tau)+\overline{B}^-(\tau)+B^-(\tau)+\overline{B}^+(\tau)}{R^+(\tau)+\overline{R}^-(\tau)+R^-(\tau)+\overline{R}^+(\tau)}} , \tag{4}$$

computed by simulation from the background rates $\overset{(-)}{B}{}^{\pm}(\tau)$, and the associated signal $\overset{(-)}{R}{}^{\pm}(\tau)$ (Eqs. 1 and 2).

The diluted asymmetry $A_{\Delta m}(\tau) \times f_b(\tau)$, folded with the decay time resolution, is fitted to the real data asymmetry $A_{obs}(\tau)$ leaving Δm and $\mathrm{Re}(x)$ as free parameters:

$$A_{\Delta m}(\tau) \times f_b(\tau) = A_{obs}(\tau) \ . \tag{5}$$

In order to reduce the systematic error related to the background knowledge, and to minimize the correlation between Δm and $\mathrm{Re}(x)$, the fit is performed above 2 τ_S. The value of $\mathrm{Re}(x)$ resulting from the fit is $Re(x) = (12.4 \pm 11.9_{stat}) \times 10^{-3}$ and we obtain $\Delta m = (0.5274 \pm 0.0029_{\mathrm{stat.}}) \times 10^{10}\hbar/\mathrm{s}$. The correlation coefficient between Δm and $\mathrm{Re}(x)$ is 0.068, and the value and the error of Δm do not change by fixing the value of $\mathrm{Re}(x)$ to zero. The asymmetry $A_{\Delta m}$ (eq. 3) is plotted in Fig. 4, using the value of Δm found by the fit, together with the data points corrected for $f_b(\tau)$.

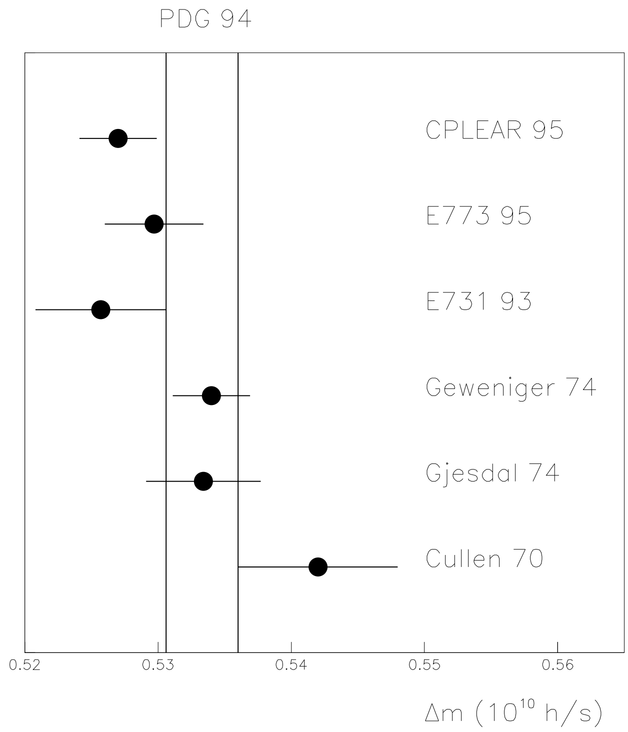

Figure 5: Δm values from CPLEAR[9] and other experiments[4,5]. The two vertical lines correspond to the PDG '94 value $\pm 1\sigma$.

Table 1: Systematic errors

Source of systematic error	Known precision	$\Delta(\Delta m)$ $[10^{10}\hbar/\mathrm{s}]$
background level	$\pm 10\%$	± 0.0004
background asymmetry	$\pm 1.0\%$	± 0.0001
decay time resolution	$\pm 10\%$	± 0.0001
η correction	$\pm 2.5\%$	± 0.0001
τ_S precision [4)]	$\pm 0.0012 \times 10^{-10}\mathrm{s}$	± 0.0001
total		± 0.0005

The systematic errors of the measurement are listed in Table 1. The main source of systematic uncertainty arises from the Monte Carlo estimation of the background, in particular at short decay times, where the $\pi^+\pi^-$final state has to be rejected by a large factor ($> 10^3$).

The simulation shows that, for all the background channels, the misidentification of a pion as an electron results from a large error in the track momentum evaluation. To check our simulation, we have relaxed the cuts on the $\pi^+\pi^-$channel so that the background becomes comparable to the signal. The simulation still agrees with the data within 10%. We can thus assume a 10% accuracy on the estimation of the various types of background which are used to compute the background dilution factor $f_b(\tau)$.

A possible charge asymmetry in the remaining background has been studied with the pion data used to calibrate the e/π separation [3]. This sample shows a difference of (3.0 ± 1.0)% between the number of π^+which are misidentified as positrons and the number of π^-which are misidentified as electrons. This asymmetry is taken into account in the fit and the corresponding uncertainty on Δm is $0.0001 \times 10^{10}\hbar/s$.

Folding the decay time resolution in the $A_{\Delta m}$ asymmetry resulted in a shift of $+0.0009 \times 10^{10}\hbar/s$ to the value of Δm. The uncertainty on this correction due to the Monte Carlo statistics is $\pm 0.0001 \times 10^{10}\hbar/s$. In conclusion, our final result [3] is

$$\mathbf{\Delta m} = (\mathbf{0.5274} \pm \mathbf{0.0029}_{\mathrm{stat.}} \pm \mathbf{0.0005}_{\mathrm{syst.}}) \times \mathbf{10^{10}}\hbar/\mathrm{s}, \quad (6)$$

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

which does not depend on the value of ϕ_{+-} and is the most precise value obtained using semileptonic final states [4], see Fig. 5. Adding this new value and the most recent one [5] to the previous values used by the PDG [4], we obtain

$$\Delta m = (0.5310 \pm 0.0019) \times 10^{10}\hbar/\mathrm{s}$$

where the error is scaled by a factor 1.2 following the PDG procedure.

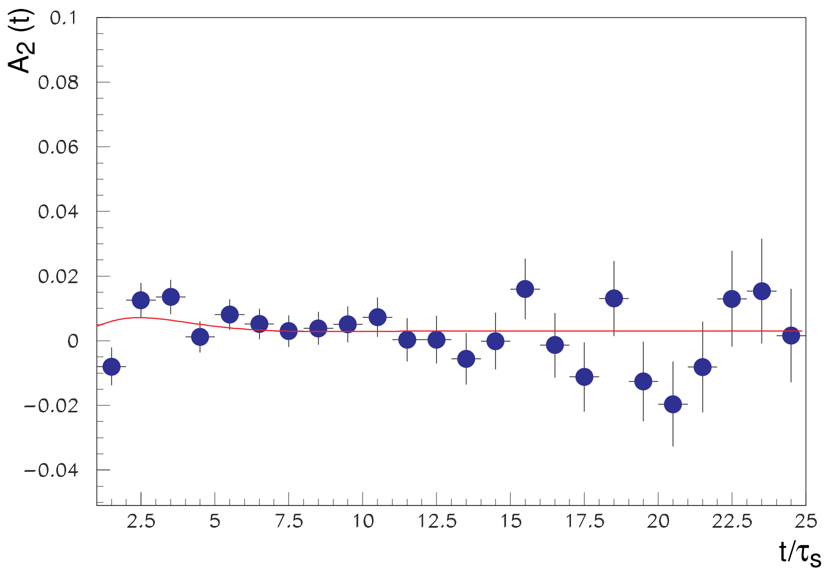

Figure 6: The asymmetry $A_2(t)$ vs the decay time. The line represents the result of the fit.

The asymmetry $A_2(t)$ is sensitive to $Im(x)$ and is shown in Fig. 6,

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

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

where $\gamma = (\gamma_S + \gamma_L)/2$, $Re(x) = 0$ and $\delta_{CPT} = 0$ and ε_T describes CP violation in the kaon matrix. The fit yields:

$$\mathbf{Im(x) = (4.8 \pm 4.3_{stat} \pm 0.6_{syst}) \times 10^{-3}} \tag{7}$$

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

4 $K^\circ(\overline{K}^\circ) \rightarrow \pi^+\pi^-$ decay mode.

The rates for initially pure K^0 and $\overline{K}^0$ decaying into the $\pi^+\pi^-$ final state, $R(\tau)$ and $\overline{R}(\tau)$ respectively, can be expressed as a function of the decay eigentime τ by:

$$R(\tau), \overline{R}(\tau) \propto \frac{1 \mp 2\mathrm{Re}(\varepsilon_\mathrm{T})}{2} \left[e^{-\tau/\tau_\mathrm{S}} + |\eta_{+-}|^2 e^{-\tau/\tau_\mathrm{L}} \pm 2|\eta_{+-}| e^{-\frac{1}{2}(\tau/\tau_\mathrm{L} + \tau/\tau_\mathrm{S})} \cos(\Delta m \tau - \phi_{+-}) \right], \tag{8}$$

where $\tau_\mathrm{L}(\tau_\mathrm{S})$ is the $\mathrm{K_L}(\mathrm{K_S})$ mean life and ε_T describes CP violation in the kaon mixing matrix. Since $R(\tau)$ and $\overline{R}(\tau)$ are the decay rates of CP conjugate hadronic final states, any difference between the two is a sign of CP violation. In Fig.7 the decay rates measured by our experiment are shown separately for K^0 and $\overline{K}^0$. Such a difference between the behavior in the world and the antiworld, where the world observed in the "CP-mirror" is referred to as the antiworld, is first direct demonstration of the known violation of CP-invariance graphically.

The $\mathrm{K_L}$–$\mathrm{K_S}$ interference term in Eq.8 is isolated by forming the asymmetry of the observed number of K^0 and $\overline{K}^0$ decays to $\pi^+\pi^-$, $N(\tau)$ and $\overline{N}(\tau)$, as a function of the decay time:

$$A_{+-}(\tau) = \frac{\overline{N}(\tau) - \alpha N(\tau)}{\overline{N}(\tau) + \alpha N(\tau)} = -2 \frac{|\eta_{+-}| e^{\frac{1}{2}(\tau/\tau_\mathrm{S} - \tau/\tau_\mathrm{L})} \cos(\Delta m \tau - \phi_{+-})}{1 + |\eta_{+-}|^2 e^{(\tau/\tau_\mathrm{S} - \tau/\tau_\mathrm{L})}}. \tag{9}$$

The acceptances common to K^0 and $\overline{K}^0$ cancel in the asymmetry, thus reducing the systematic uncertainties. The normalization factor α includes the tagging efficiency ξ of $\overline{K}^0$ relative to K^0, $\alpha \simeq [1 + 4\mathrm{Re}(\varepsilon)] \times \xi$, and is determined from the data together with the CP violation parameters $|\eta_{+-}|$ and ϕ_{+-}.

In addition to online and offline event selections, a kinematical and geometrical fit with nine constraints is imposed on the events. These constraints require conservation of energy and momentum, the missing mass at the annihilation vertex to be equal to the K^0 mass, the intersections of two track helices at the annihilation and decay vertices, respectively, and the K^0 momentum to be colinear with the line joining the two vertices. The fit improves the signal–to–background ratio and the decay–time resolution. A simulation study of the detector shows this resolution varying from 4 ps to 10 ps as a function of the neutral kaon decay radius. The only remaining background source consists of semileptonic decays, which are further reduced by using electron identification [2]. Figure 8 shows the sum of the decay–time distributions of K^0's and $\overline{K}^0$'s in which the $\mathrm{K_S}$–$\mathrm{K_L}$ interference cancels. A fit of the expected kaon decay rate and the background shape (Fig. 5, open circles) yields a value for the $\mathrm{K_S}$ mean life in agreement (within 1%) with the world average value [4]. The background level obtained with this fit is in good agreement with Monte Carlo calculations based on known branching ratios. A total of 1.6×10^7 $K^0(\overline{K}^0) \rightarrow \pi^+\pi^-$ events in the time interval between $1\tau_S$ and $20\tau_S$ remain after background subtraction (only a small fraction of the data with decays below $1\,\tau_\mathrm{S}$ has been analysed).

In the absence of experimental data for the difference between the forward scattering amplitudes of K° and $\overline{K}^\circ$ in the momentum region of the present experiment (<800 MeV/c), we have used the values calculated recently by Eberhard and Uchiyama [6]. The values used for hydrogen as input to their calculation on heavy nuclei are consistent with others [7], from which we estimate an average uncertainty smaller than 13% on the magnitude and 9° on the phase for hydrogen and for heavy nuclei [8]. We have corrected our data on an event–by–event basis depending on the measured momentum of the neutral kaon as well as on the detector materials traversed (see [8]). Diffractive regeneration and absorption are found to be negligible in our experimental set–up. In 1996 a dedicated measurement of the difference of the $K^\circ - \overline{K}^\circ$ forward

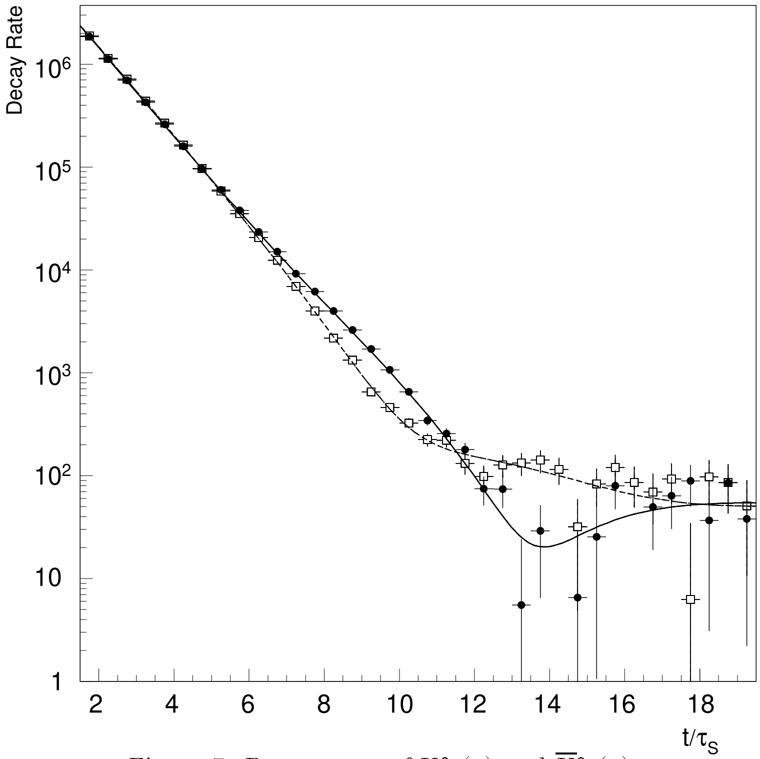

Figure 7: Decay rates of K^o (•) and $\overline{K}^o$ (∘).

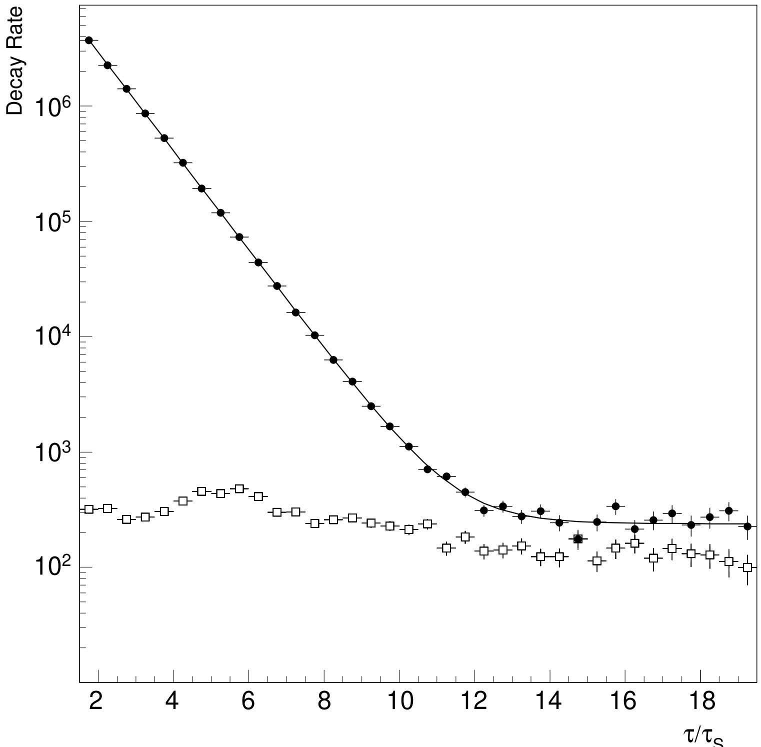

Figure 8: Sum of K^o and $\overline{K}^o$ decay rates (●) (normalized and corrected for $K \to \pi^+\pi^-$ acceptance). The solid line is a fit with two exponential functions for K_S and K_L, and the background distribution (□) obtained from a simulation.

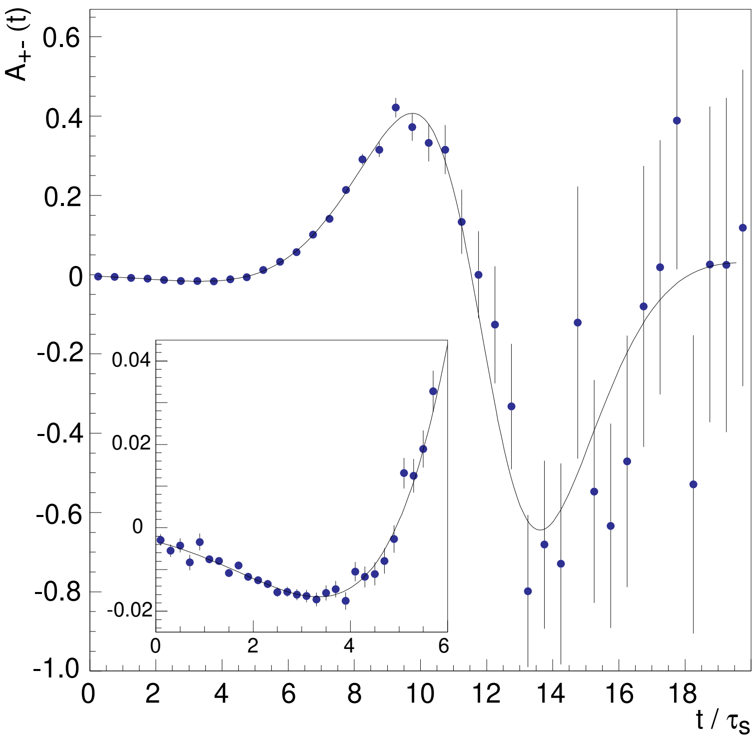

Figure 9: The asymmetry A_{+-} vs the decay time. The solid line represents the result of the fit.

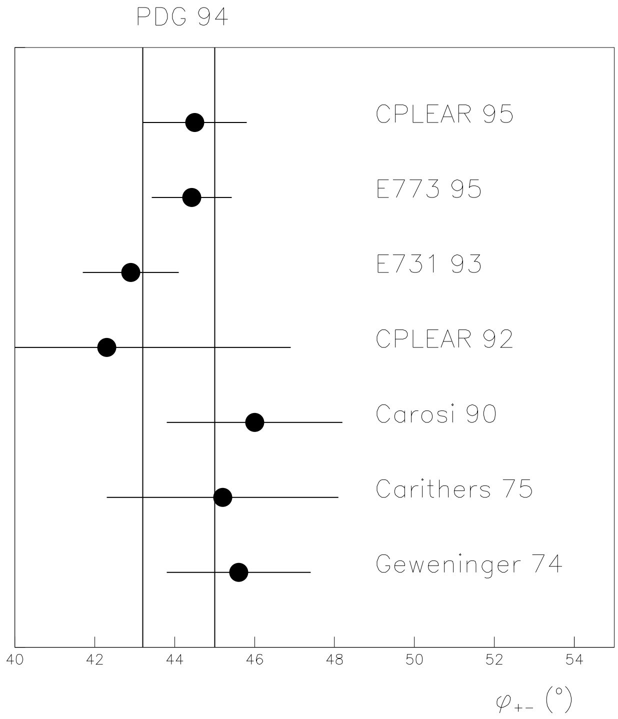

Figure 10: φ_{+-} values from CPLEAR[10,11] and other experiments[4,5]. The two vertical lines correspond to the PDG '94 value $\pm 1\sigma$. We note that K.Kleinknecht et al. [Phys. Let.336B (1995) 581] claims that the systematic error of E731 and E773 should be increased due to regeneration corrections. These claims, however, have been responded to in the literature [R.A.Briere and B.Winstein, Phys. Rev. Lett. 75 (1995) 402].

scattering amplitudes in carbon at low momentum will be done with the CPLEAR detector [9]. After this measurement the systematic error on φ_{+-} due to regeneration effects is expected to decrease by a factor more than 2.

Figure 9 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 K° relative to $\overline{K}^\circ$ (determined at short decay-times) and for regeneration effects. The K° and $\overline{K}^\circ$ tagging efficiences are not equal due to the different interactions of K^+ and K^-, and of π^+ and π^-, in the detector material.

Equation 9 folded with the decay time resolution is fitted to the asymmetry shown in Fig.9 with $|\eta_{+-}|$, ϕ_{+-} and α as free parameters. The values of ϕ_{+-} and $|\eta_{+-}|$ obtained by the fit, together with their dependence on Δm (in units of $10^7\,\hbar\,\mathrm{s}^{-1}$) and τ_S (in units of ps), are:

$$|\eta_{+-}| = (2.312 \pm 0.043 - 0.001[\Delta m - 527.4] + 0.091[\tau_S - 89.26]) \times 10^{-3} \tag{10}$$

$$\phi_{+-} = 42.7 \pm 0.9^\circ + 0.316[\Delta m - 527.4]^\circ + 0.30[\tau_S - 89.26]^\circ, \tag{11}$$

where we used $\Delta m = (527.4 \pm 2.9) \times 10^7 \hbar\,\mathrm{s}^{-1}$ measured recently by the CPLEAR collaboration using semileptonic decays [3] (see section 2) and $\tau_S = (89.26 \pm 0.12)\,\mathrm{ps}$ [4]. The correlation coefficient between ϕ_{+-} and $|\eta_{+-}|$ given by the fit is 12%. Floating Δm in the fit gives $\mathbf{\Delta m = (529.5 \pm 6.7) \times 10^7}\hbar\,\mathrm{s}^{-1}$, in good agreement with the value used. By changing the background level, the decay time resolution, the regeneration amplitude, Δm and τ_S within their estimated uncertainties we derive the systematic errors shown in Table 2. Our results are [10]:

$$|\eta_{+-}| = (\mathbf{2.312 \pm 0.043}_{\mathrm{stat.}} \pm \mathbf{0.030}_{\mathrm{syst.}} \pm \mathbf{0.011}_{\tau_S}) \times \mathbf{10^{-3}} \tag{12}$$

$$\phi_{+-} = 42.7^\circ \pm 0.9^\circ_{\mathrm{stat.}} \pm \mathbf{0.6}^\circ_{\mathrm{syst.}} \pm \mathbf{0.9}^\circ_{\mathbf{\Delta m}} \,. \tag{13}$$

$$\alpha = 0.9989 \pm 0.0006$$

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. Our systematic errors result mainly from the present uncertainty on the difference between the forward scattering amplitudes of K^0 and $\overline{K}^0$ and the uncertainty on the value of Δm.

The value of ϕ_{+-} obtained with our value of Δm agrees well with the superweak phase computed with the same Δm and $\Delta\Gamma$ from [4]:

$$\phi_{\mathbf{SW}} = \tan^{\mathbf{-1}} \frac{\mathbf{2\Delta m}}{\Delta\Gamma} = \mathbf{43.30^\circ \pm 0.16^\circ}, \tag{14}$$

being consistent with CPT symmetry.

Table 2: Systematic errors of the presented ϕ_{+-} and $|\eta_{+-}|$ values

Source	ϕ_{+-}	$\lvert\eta_{+-}\rvert \times 10^3$
Background level	0.05^0	0.02
Decay time resolution	0.10^0	0.01
Normalization procedure	0.05^0	0.005
Regeneration	0.60^0	0.02
Total syst.	$\mathbf{0.61^0}$	**0.030**
$\sigma(\Delta m)$	0.92^0	0.003
$\sigma(\tau_S)$	0.04^0	0.011

Using the PDG [4] value of $\Delta m = (533.3 \pm 2.7) \times 10^7 \hbar\,\mathrm{s}^{-1}$, we find $|\eta_{+-}| = 2.311 \times 10^{-3}$ and $\phi_{+-} = 44.5^\circ$. The errors remain the same except for the error on ϕ_{+-} resulting from the uncertainty of Δm which reduces to 0.8°.

Figure 10 shows our result on φ_{+-} in comparison with previous measurements[4,5] for the same Δm value [4].

5 The correlation of the φ_{+-} measurements from Δm.

The comparison of the phase ϕ_{+-} of the CP violation parameter η_{+-} with the superweak phase $\varphi_{SW} \equiv \tan^{-1}(2\Delta m/\Delta\Gamma)$, yields the world's best limits of CPT violation. The phase ϕ_{+-} has been measured by many experiments over the last 30 years. It is important to notice that the experimental value of φ_{+-} has a different dependence on Δm for different experiments. Averaging Δm and ϕ_{+-} independently [4] is not an adequate method as these two parameters are correlated. We have evaluated both parameters, Δm and ϕ_{+-} by taking into account the correlations. Since the values of ϕ_{+-} depend on the value of $\tau_{\rm S}$, we leave $\tau_{\rm S}$ as an additional free parameter in the fit. However its value is constrained to the world average of $<\tau_{\rm S}>= (0.8926 \pm 0.0012) \times 10^{-10}\,{\rm s}$ [4].

Using as input to our fit the experimental data published up to 1994, we find similar results as the independent averaging method of PDG [4] although our error for $<\Delta m>$ is smaller compared to the PDG result due to the additional information used, and in contrast to PDG we do not need to scale the error of Δm by 1.2 since the χ^2/degree of freedom (dof) for the combined average of ϕ_{+-} and Δm is 1.0, For Δm we find $<\mathbf{\Delta m}>= (\mathbf{532.2 \pm 1.8 \pm 0.1}) \times \mathbf{10^7}\hbar/{\rm s}$ and for ϕ_{+-} the value $<\phi_{+-}>= \mathbf{44.5^\circ \pm 1.0^\circ \pm 0.1^\circ}$, where the second error reflects the uncertainty of the correlation between ϕ_{+-} and Δm.

I believe that a complete evaluation of Δm and ϕ_{+-} from a correlation analysis of the different experiments including the two Δm values [3, 10] and the ϕ_{+-} value [10], from CPLEAR as well as the Δm and ϕ_{+-} value from E773 [5] will improve considerably both the precisions on $\phi_{+-} - \phi_{SW}$ and the agreement of the data with the CPT invariance.

6 Indirect CPT test.

From our present knowledge of weak interactions, the three discrete symmetries C, P and T are not exact symmetries in our universe, and the same applies to the combined symmetries CP, CT and PT. This fact is well accomodated in the Standard Model and is well established experimentally. However, in the framework of a local field theory of Lorenz invariance any order of the triple product CPT represents an exact symmetry. In some cases as spontaneously broken symmetries with degenerated vacuum, fields with infinite many components and non local theories, the CPT invariance could be in first or higher order not exact.

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° [19] 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 component of the CPT violation parameter δ 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:

$$\varphi_0 = \frac{\gamma_L}{\gamma_S}[2BR({\rm K_L} \to \pi l\nu)Im(x) + BR({\rm K_L} \to 3\pi)Im(\eta_{3\pi} - \eta_{+-})]$$

The term ϵ' describes the CP violation in the decay amplitude and can be neglected since $|\epsilon'| < 10^{-5}$ [20] and the phase difference between the isospin two (δ_2) and zero (δ_0) amplitudes is [4] $(\delta_2 - \delta_0) = (-45 \pm 15)^\circ$). Figure 11 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:

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

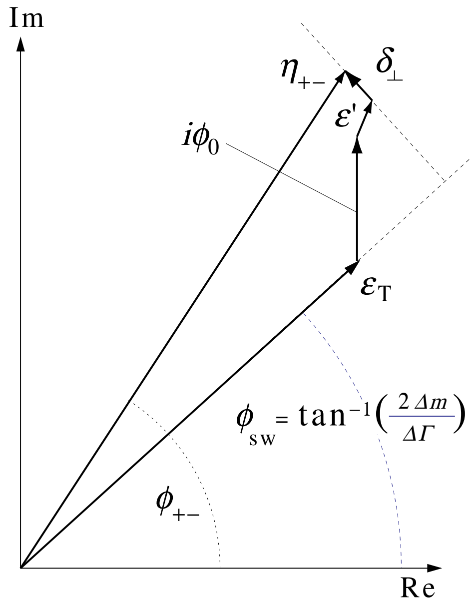

Figure 11: The relation between the CP violating parameters η_{+-}, ϵ_T, $\delta_\perp$, φ_0 and ϵ'.

Assuming CPT conservation in the decay amplitude related to the smallness of $\phi_{+-} - \phi_{00}$ [4)], we obtain the preliminary value from the present CPLEAR results:

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

This is the best limit on a particle-antiparticle mass difference arising from the measurements of one single experiment without any phenomenological assumption on any parameter.

Results from the comparison of ϕ_{+-} with ϕ_{00} are used frequently as a test of CPT invariance. Here I would like to make clear that the measurement of $(\phi_{+-} - \phi_{00})$ test only the CPT invariance in the decay, i.e. the CPT violating components of $\epsilon\prime$, but the measurement of $\phi_{+-} - \phi_{SW}$ is testing the combined effect of both the CPT violating component δ and ReB_2/ReA_0 [12, 13)] Referring to the work of Barmin et al. [12)] we stress that only for the case of $|\epsilon\prime| \neq 0$, the measurement of the phase difference $\phi_{+-} - \phi_{00}$ provides a test for the CPT violating decay parameters. Even if $\phi_{+-} - \phi_{00}$ could be measured to be exactly zero, this would not allow any conclusion to be drawn regarding CPT invariance [13)]. Therefore, for the case of very small or vanishing values of $|\epsilon\prime|$, the best and more complete test of CPT invariance [13)] is the phase difference of η_{+-} relative to the superweak angle, i.e. $(\phi_{+-} - \phi_{SW})$.

7 Separate CPT and T violation.

The most accurate CPT tests, such as lifetime and mass equalities between particles and antiparticles, do not verify the full extent of CPT invariance since they do not involve helicity or complex conjugation [14)]. The neutral kaon complex is a superior tool for making detailed tests of CPT symmetry [14)].

Many authors have dealt with the description of the K°-$\overline{K^\circ}$ complex and with many consequences of CP, T and CPT violation [14)]. The Wigner-Weisskopf approximation is usally used to obtain the evolution in time of the system. After Lee, Oehme and Yang [15)], it is customary to consider the total number of neutral K-mesons as a function of time, starting initially with pure K° (or $\overline{K^\circ}$),

$$\begin{aligned} N^{\pm}(t) = \frac{1}{2}[[1 \mp 2Re(\varepsilon_T + \delta)]exp[-\gamma_L t] + [1 \mp 2Re(\varepsilon_T - \delta)]exp[-\gamma_S t] \\ \pm 2[(Re\varepsilon_T + iIm\delta)exp[i\Delta m t] + c.c.]exp[-\frac{1}{2}(\gamma_L + \gamma_S)t]] \end{aligned} \tag{15}$$

where γ_S^{-1},γ_L^{-1} are the K_S, K_L lifetimes, Δm their mass difference, δ the Lee-Wu CPT violation parameter ($\delta = 0$ for CPT conservation) and ε the T violation parameter. The upper sign is for K°, and the lower for $\overline{K}^\circ$.

Clearly, a measurement of the coefficients in eq. 15 will give combinations of ε and δ and will enable one to deduce values for these parameters. In particular, the reversal of sigh of δ in the oscillation term implied by CPT was often proposed as a test for CPT invariance. But, as noted by Michel [16], T may simulate a similar effect when the CPT violation is small. The effect would be much more decisive had terms with ε and with δ been separated.

Given the capacity of CPLEAR the fractional numbers of K° or of $\overline{K}^\circ$ particles in the beam may be calculated:

$$R^{K^\circ}(K^\circ, t) = |<K^\circ|\psi^{K^\circ}(t)>|^2 = \frac{1}{4}[(1-4Re\delta)exp[-\gamma_L t] + (1+4Re\delta)exp[-\gamma_S t] + 2[cos(\Delta m t) - 4Im\delta sin(\Delta m t)]exp[-\frac{1}{2}(\gamma_L+\gamma_S)t] \tag{16}$$

$$R^{K^\circ}(\overline{K}^\circ, t) = |<\overline{K}^\circ|\psi^{K^\circ}(t)>|^2 = \frac{1}{4}(1-4Re\varepsilon_T)(exp[-\gamma_L t] + exp[-\gamma_S t] - 2cos(\Delta m t)exp[-\frac{1}{2}(\gamma_L+\gamma_S)t]) \tag{17}$$

In these equations, $|\psi^{K^\circ}(t)>$ is the state vector starting from pure K° at $t = 0$. $R^{K^\circ}(K^\circ, t)$ denotes the fractional number of K°'s in this beam, while $R^{K^\circ}(\overline{K}^\circ, t)$ denotes the fractional number of $\overline{K}^\circ$'s in it at the proper time t. The change of K° to $\overline{K}^\circ$ in all expressions will cause the change of signs of both ε and δ.

Clearly, the sum of eqs. 16 and 17 gives eq. 15. The obvious advantage from CPLEAR (eqs. 16 and 17) lies in the separation of the CPT parameter δ and the T parameter ε_T. A measurement of these quantities may thus serve as the independent test of T violation and CPT invariance.

The CPLEAR experiment, assuming the validity of the $\Delta S = \Delta Q$ rule, can perform the experimental measurement of the ratio between the first two coefficients of eq. 16, which is independent of the flux of the beam, which will give directly $Re\delta$, and the oscillating term will give $Im\delta$. A measurement of the flux in eq. 17 will give $Re(\varepsilon_T)$.

8 Direct measurement of T violation (Kabir test).

Since weak interactions do not conserve strangeness (hypercharge), a K° meson can, and does occasionally, transform itself into a $\overline{K}^\circ$ meson in the course of time. Similarly, a state produced initially as $\overline{K}^\circ$ may be found later to have changed into K°. Time reversal invariance, or microscopic reversibility (sometimes also called reciprocity) would require, as proposed by Kabir, all details of the second process to be deducible from the first; in particular, it should proceed at a rate exactly equal to that of the $K^\circ \to \overline{K}^\circ$ transformation, since time reversal simply reverses the process in this case.

A convenient way to make the measurement is to take advantage of the $\Delta S = \Delta Q$ rule. Then $\pi^- l^+ \nu$ and $\pi^+ l^- \overline{\nu}$ decays in a neutral kaon beam provide indicators of the K° and $\overline{K}^\circ$ content, respectively. The first could be used in decays of a beam produced initially as $\overline{K}^\circ$ to measure $\overline{K}^\circ \to K^\circ$ conversion while the second would similary yield the rate of $K^\circ \to \overline{K}^\circ$ transitions. Therefore, we are able to compare the probability $|<K^\circ|M - i\Gamma|\overline{K}^\circ>|^2$ to the probability $|<\overline{K}^\circ|M - i\Gamma|K^\circ>|^2$ by forming the asymmetry using eq. 17:

$$A_T(t) \equiv \frac{\overline{R}^+(t) - R^-(t)}{\overline{R}^+(t) + R^-(t)} \tag{18}$$

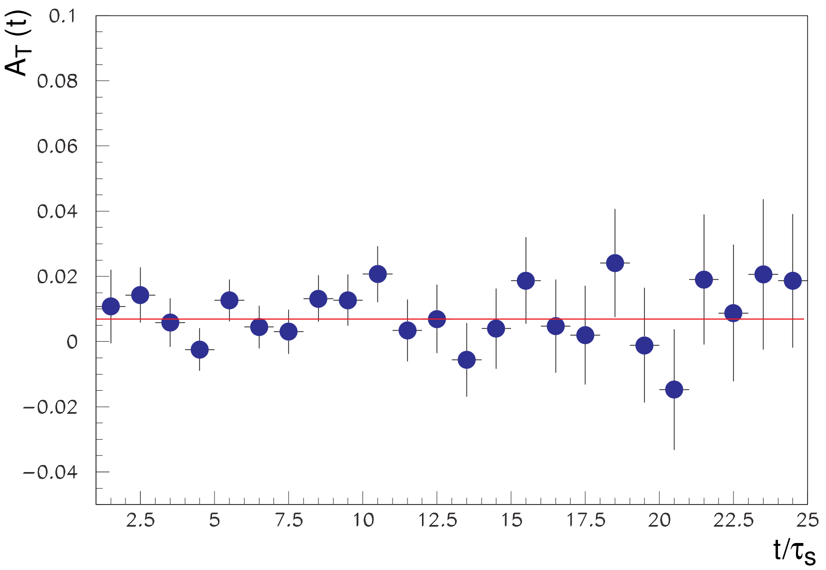

Figure 12: The asymmetry $A_T(t)$ vs the decay time. The line represents the result of the fit.

where the parameter x is assumed to be zero and M and Γ are the usual mass and decay matrix respectively, as defined in the textbooks. These probabilities are related as:

$$\begin{aligned} < \mathrm{K^o}|M - i\Gamma|\overline{\mathrm{K}}^\mathrm{o} >=< T\mathrm{K^o}|T(M - i\Gamma)|\overline{\mathrm{K}}^\mathrm{o} >^*= \\ < T\mathrm{K^o}|T(M - i\Gamma)T^{-1}|T\overline{\mathrm{K}}^\mathrm{o} >^*=< T\mathrm{K^o}|(TMT^{-1}) + i(T\Gamma T^{-1})|T\overline{\mathrm{K}}^\mathrm{o} >^*= \\ < T\overline{\mathrm{K}}^\mathrm{o}|(TMT^{-1})^\dagger + (iT\Gamma T^{-1})^\dagger|T\mathrm{K^o} >=< T\overline{\mathrm{K}}^\mathrm{o}|(M_T)^\dagger + (i\Gamma_T)^\dagger|T\mathrm{K^o} >= \\ < T\overline{\mathrm{K}}^\mathrm{o}|M_T - i\Gamma_T|T\mathrm{K^o} >=< \overline{\mathrm{K}}^\mathrm{o}|M_T - i\Gamma_T|\mathrm{K^o} > \end{aligned} \tag{19}$$

with $M_T(\Gamma_T) = TM(\Gamma)T^{-1}$ and $|\mathrm{K^o} >= T|\mathrm{K^o} >$, $|\overline{\mathrm{K}}^\mathrm{o} >= T|\overline{\mathrm{K}}^\mathrm{o} >$ within a phase angle. These probabilities are equal if the underlying theory is invariant under T transformation without any additional assumption on CPT inavriance. Figure 12 shows the asymmetry $A_T(t)$. A fit to this asymmetry gives:

$$\mathbf{A_T = (6.3 \pm 2.1_{stat} \pm 1.8_{syst}) \times 10^{-3}} \tag{20}$$

It is important that time reversal invariance can be checked directly because everyone beleives T is violated, although no empirical evidence existed for this. The effect of T violation is expected at level of 10^{-3} since CP is known to be violated at this degree and everyone believes CPT invariance is exact, although there is no evidence for this either.

9 Direct test of CPT invariance in the K° - $\overline{\mathrm{K}}$° mixing.

CPT invariance implies, independent of T invariance, that $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$. By using $|\overline{\mathrm{K}}^\mathrm{o} >= CPT|\mathrm{K^o} >$ within an arbitrary phase and similarely to eqs. 19, it can be proven that the asymmetry:

$$A_{CPT}(t) \equiv \frac{\overline{R}^-(t) - R^+(t)}{\overline{R}^-(t) + R^+(t)} \tag{21}$$

is a direct measure of CPT-violation, where we used $x = 0$ and eq. 16. This is because CPT invariance requires that the fraction of K°'s which survive as K° is exactly equal to that of $\overline{\mathrm{K}}$°'s which remain $\overline{\mathrm{K}}^\circ$. A fit to $A_{CPT}(t)$ for large life times gives for $Re(\delta_{CPT})$ a preliminary value compatible with zero,

$$\mathbf{Re}(\delta_{\mathbf{CPT}}) = (\mathbf{0.07} \pm \mathbf{0.53_{stat}} \pm \mathbf{0.45_{syst}}) \times \mathbf{10^{-3}} \tag{22}$$

For short lifetimes eq. 21 is sensitive also to $Im(\delta_{CPT})$ but the analysis has not yet finished.

10 $\mathrm{K}^\circ(\overline{\mathrm{K}}^\circ) \to \pi^+\pi^-\pi^\circ$ 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 $\mathrm{K_L} \to \pi^+\pi^-\pi^\circ$ is CP-allowed when the final state is the kinematically preferred $l = 0$ state, while the decay $\mathrm{K_S} \to \pi^+\pi^-\pi^\circ$ is a mixture of CP-violating, $l = 0$, and CP-conserving, but kinematically suppressed, $l = 1$ transitions. However, any observation of an interference effect in these decays is, according to the theorem of ref. [17], a direct prove of CP violation. 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 $\mathrm{K_S}$ contribution cancels in the $\mathrm{K_S K_L}$ interference. The time dependent asymmetry:

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

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

is shown in Fig. 13. The total number of events is 1.5×10^5. From a fit to this asymmetry we obtain as preliminary result:

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

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

The value of $Re(\eta_{+-0})$ is consistent with been equal to $Re(\eta_{+-})$. Figure 14 shows our result, in comparison with the results from other experiments.

11 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 1996) 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.

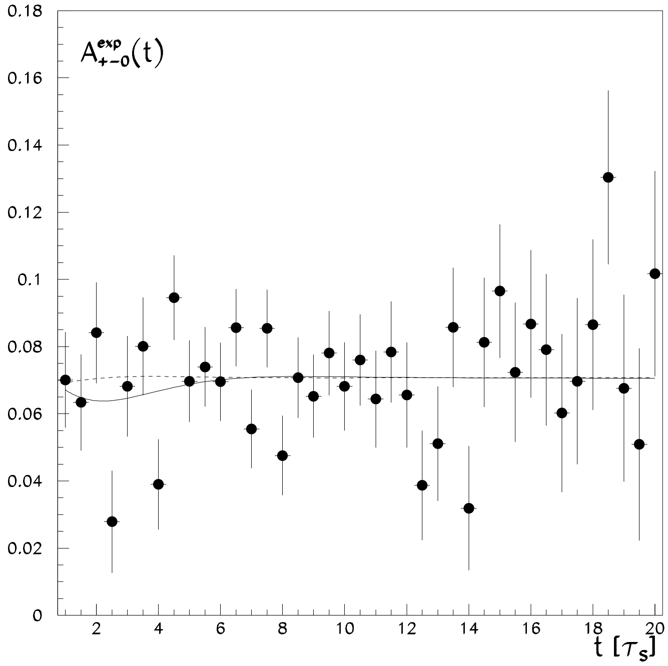

Figure 13: The asymmetry $A_{+-0}(t)$ vs the decay time. The solid (dotted) line represents the result of the fit when we float $Re(\eta_{+-0})$ and $Im(\eta_{+-0})$ (only $Im(\eta_{+-0})$ with the constraint $Re(\eta_{+-0}) = Re(\eta_{+-})$).

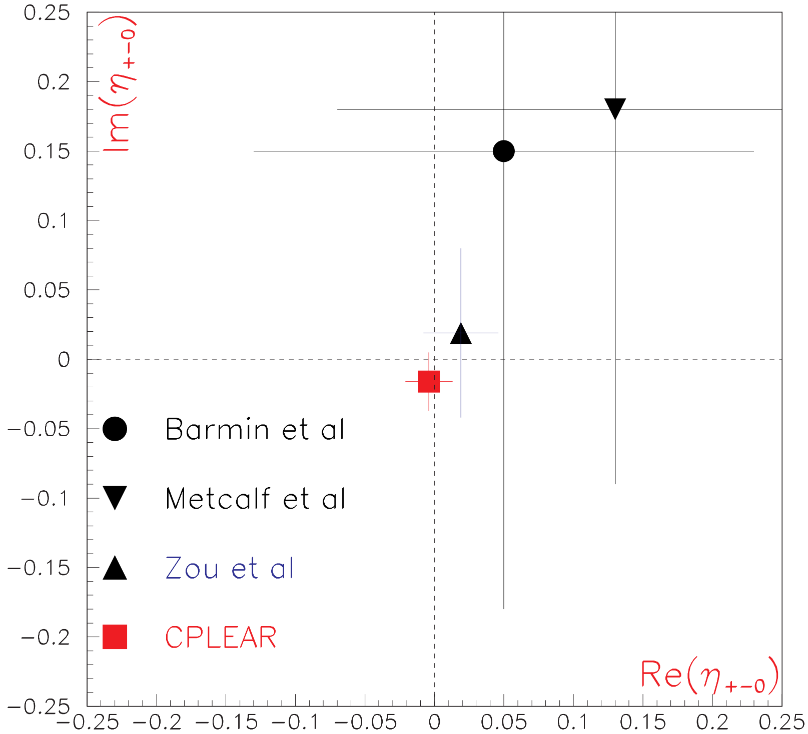

Figure 14: $Im(\eta_{+-0})$ vs $Re(\eta_{+-0})$ for CPLEAR (preliminary) and other experiments[4,18].

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