MEASUREMENT OF CP VIOLATION PARAMETERS AND TEST OF CPT INVARIANCE WITH $\overline{\mathrm{K}^0}$ AND K^0 AT LEAR.

The CPLEAR Collaboration :

R. Adler[2], T. Alhalel[11], A. Angelopoulos[1], A. Apostolakis[1], E. Aslanides[11], G. Backenstoss[2], C.P. Bee[2], O. Behnke [17], A. Benelli [9], V. Bertin[11], F. Blanc[7,13], P. Bloch[4], Ch. Bula[13], P. Carlson[15], M. Carroll[9] J. Carvalho[5], E. Cawley[9], S. Charalambous[16], M. Chardalas[16], G. Chardin[14], M.B. Chertok[3], A. Cody[9], M. Danielsson[15], S. Dedoussis[16], M. Dejardin[14], J. Derre[14], J. Duclos[14], A. Ealet[11], B. Eckart[2], C. Eleftheriadis[16], I. Evangelou[8], L. Faravel [7], P. Fassnacht[11], J.L. Faure[14], C. Felder[2], R. Ferreira-Marques[5], W. Fetscher[17], M. Fidecaro[4], A. Filipčič[10], D. Francis[3], J. Fry[9], E. Gabathuler[9], R. Gamet[9], D. Garreta[14], H.- J. Gerber[17], A. Go[15], C. Guyot[14], A. Haselden[9], P.J. Hayman[9], F. Henry-Couannier[11], R.W. Hollander[6],E. Hubert[11], K. Jon-And[15], P.-R. Kettle[13], C. Kochowski[14], P. Kokkas[2], R. Kreuger[6], R. Le Gac[11], F. Leimgruber[2],A. Liolios[16], E. Machado[5], I. Mandić[10], N. Manthos[8], G. Marel[14], M. Mikuž[10], J. Miller[3], F. Montanet[11], T. Nakada[13], A. Onofre[5], B. Pagels [17], I. Papadopoulos[16], P. Pavlopoulos[2], J. Pinto da Cunha[5], A. Policarpo[5], G. Polivka[2], R. Rickenbach[2], B.L. Roberts[3], E. Rozaki[1], T. Ruf[4], L. Sakeliou[1], P. Sanders[9], C. Santoni[2], K. Sarigiannis[1], M. Schäfer[17], L.A. Schaller[7], A. Schopper[4], P. Schune[14], A. Soares[14], L. Tauscher[2], C. Thibault[12], F. Touchard[11], C. Touramanis[4], F. Triantis[8], E. Van Beveren[5], C.W.E. Van Eijk[6], G. Varner[3], S. Vlachos[2], P. Weber[17], O. Wigger[13], M. Wolter[17], C. Yeche[14], D. Zavrtanik[10] and D. Zimmerman[3].

Presented by Christophe Yèche,
CEA, DAPNIA/Service de Physique des Particules,
CE-Saclay 91191 Gif-Sur-Yvette Cedex.

Abstract :

The CPLEAR experiment at CERN studies the CP, T and CPT symmetries in the neutral kaon system by measuring the rate asymmetries between the decays of initially pure K^0 and $\overline{\mathrm{K}^0}$ states. Using data taken between 1990 and mid 1994, precise measurements of $|\eta_{+-}|$, ϕ_{+-} and Δm are reported. The comparison of ϕ_{+-} with the superweak phase gives one of the most sensitive test of CPT invariance and leads to a new limit on the K^0-$\overline{\mathrm{K}^0}$ mass difference.

[1]University of Athens, [2]University of Basle, [3]Boston University, [4]CERN, [5]LIP and University of Coimbra, [6]Delft University of Technology, [7]University of Fribourg, [8]University of Ioannina, [9]University of Liverpool, [10]J. Stefan Inst. and Phys. Dep., University of Ljubljana, [11]CPPM, IN2P3-CNRS et Université d'Aix-Marseille II, [12]CSNSM, IN2P3-CNRS, Orsay, [13]Paul-Scherrer-Institut(PSI), [14]CEA, DSM/DAPNIA, CE-Saclay, [15]Royal Institute of Technology, KTH, Stockholm, [16]University of Thessaloniki, [17]ETH-IPP Zürich.

1 Introduction

So far, CP violation has been observed using $\mathrm{K_L}$ and $\mathrm{K_S}$ beams, in decays of neutral kaons into two-pion final states ($\pi^+\pi^-$, $\pi^0\pi^0$ [1] and recently $\pi^+\pi^-\gamma$ [2]) and in the charge asymmetry of semileptonic $\mathrm{K_L}$ decays. Rather than studying the physical states $\mathrm{K_S}$ and $\mathrm{K_L}$, the CPLEAR experiment is unique in making direct use of the flavour eigenstates $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ [3]. For the decay into two pions at the decay eigentime τ, the decay rates of initial $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ are given by :

$$\left.\begin{array}{r} R(\mathrm{K^0},\pi^+\pi^-,\tau) \\ R(\overline{\mathrm{K^0}},\pi^+\pi^-,\tau) \end{array}\right\} \propto \frac{1\mp 2Re(\varepsilon)}{2}\left[e^{-\gamma_{\mathrm{S}}\tau}+|\eta_{+-}|^2\,e^{-\gamma_{\mathrm{L}}\tau}\pm 2\,|\eta_{+-}|\,e^{\frac{-(\gamma_{\mathrm{S}}+\gamma_{\mathrm{L}})\tau}{2}}\cos(\Delta\mathrm{m}\tau-\phi_{+-})\right],$$

where γ_{S} and γ_{L} are the decay widths of $\mathrm{K_S}$ and $\mathrm{K_L}$, Δm is the mass difference between $\mathrm{K_L}$ and $\mathrm{K_S}$ and ε describes CP violation in the kaon mixing matrix. The parameter η_{+-} is defined as the ratio of the CP forbidden to the CP allowed amplitude :

$$\eta_{+-}=\frac{A(\mathrm{K_L}\to\pi^+\pi^-)}{A(\mathrm{K_S}\to\pi^+\pi^-)}=|\eta_{+-}|e^{i\phi_{+-}}.$$

The corresponding decay rate asymmetry defined as

$$A_{+-}(\tau)=\frac{R(\overline{\mathrm{K^0}},\pi^+\pi^-,\tau)-\alpha R(\mathrm{K^0},\pi^+\pi^-,\tau)}{R(\overline{\mathrm{K^0}},\pi^+\pi^-,\tau)+\alpha R(\mathrm{K^0},\pi^+\pi^-,\tau)} \tag{1}$$

is sensitive to the interference term and therefore to the magnitude and the phase of the ratio η_{+-}. The normalisation factor α is proportional to the tagging efficiency of $\overline{\mathrm{K^0}}$ relative to $\mathrm{K^0}$ and is determined from the data. $A_{+-}(t)$ is related to the parameters $|\eta_{+-}|$ and ϕ_{+-} through the equation :

$$A_{+-}(\tau)=-\frac{2\,|\eta_{+-}|\,e^{\frac{(\gamma_{\mathrm{S}}-\gamma_{\mathrm{L}})\tau}{2}}\cos(\Delta\mathrm{m}\tau-\phi_{+-})}{1+|\eta_{+-}|^2\,e^{(\gamma_{\mathrm{S}}-\gamma_{\mathrm{L}})\tau}} \tag{2}$$

With a typical decay length of ~ 2.5 cm for the $\mathrm{K_S}$ the interference pattern is fully contained inside the CPLEAR detector, and we can extract a precise value of $|\eta_{+-}|$ and ϕ_{+-} from the measurement of this asymmetry. Analogous asymmetries are constructed in the case of $\pi^+\pi^-\pi^0$ and $\pi e\nu$ final states allowing different tests of the discrete symmetries (T, CP, CPT). We report here the precise measurement of the phase of η_{+-}. A comparison of the phase ϕ_{+-} with the superweak phase $\phi_{\mathrm{SW}}=\arctan(2\Delta\mathrm{m}/(\gamma_{\mathrm{S}}-\gamma_{\mathrm{L}}))$ provides one of the most sensitive test of CPT invariance. The measurement of ϕ_{+-} is strongly correlated to the value of the $\mathrm{K_L}-\mathrm{K_S}$ mass difference Δm. A precise measurement of Δm is obtained in the CPLEAR experiment with semileptonic decays and this new value of Δm is used in equation (2) to determine ϕ_{+-} when fitting it to the data.

2 The CPLEAR experiment

The CPLEAR experiment uses an intense $200\ \mathrm{MeV}/c$ antiproton beam ($\approx 10^6$ $\overline{\mathrm{p}}$/s) from the Low Energy Antiproton Ring (LEAR) at CERN. The $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ mesons are symmetrically produced in proton-antiproton annihilations at rest through the reactions

$$\begin{array}{lcll} p\overline{p} & \to & \mathrm{K^-}\pi^+\mathrm{K^0}, & \mathrm{Br}=2\times 10^{-3} \\ p\overline{p} & \to & \mathrm{K^+}\pi^-\overline{\mathrm{K^0}}, & \mathrm{Br}=2\times 10^{-3}\,. \end{array} \tag{3}$$

The strangeness of the neutral kaon is tagged by observing the sign of the charged kaon. The symmetrical production of $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ together with a symmetrical detection of their decay states have the advantage of minimizing the systematic effects.

The detector[4] has a cylindrical geometry and is mounted inside a solenoid of 3.6 m length and 1m radius, which produces a magnetic field of 0.44 T parallel to the antiproton beam. The antiprotons stop and annihilate inside a target filled with gaseous hydrogen at 16 bar pressure. The charged particle tracking is performed with two Multiwire Proportional Chambers, followed by six Drift Chambers and two layers of Streamer Tubes. All tracking devices provide a fast online position coordinate for trigger processors. The charged kaons and pions are identified using the Particle Identification Detector (PID) [5], consisting of a Scintillator-Čerenkov-Scintillator sandwich (SCS). The threshold for producing light in the Čerenkov counter is 300 MeV/c for pions and 700 MeV/c for kaons. Therefore $\mathrm{K}^{\pm}$ mesons produced in the reactions (3) with momenta less than 700 MeV/c are required to have a $S\overline{C}S$ pattern in the PID. Finally, there is an 18-layer gas sampling electromagnetic calorimeter (6.2 radiation lengths) with a high spatial resolution.

Because of the small branching ratio of the desired channels (3), the experiment requires a high annihilation rate. In order to provide an efficient online event selection and background rejection, a sophisticated multi-level trigger has been designed. The maximum trigger decision time is around 34 μs and the trigger rejection factor is about 1000. At a beam intensity of 1 MHz, the data acquisition system writes about 450 events per second on tape.

3 Data analysis

The offline analyses of $\pi^+\pi^-$ and semileptonic events are very similar. For both, the event selection requires a four track topology with a kaon candidate of momentum larger than 350 MeV. The events are then passed through kinematical and geometrical constraint fits to minimize the background and to improve the resolution of the measured K^0 decay eigentime (0.05 τ_{S} after constrained fits). These constraints require conservation of energy and momentum, the missing mass at the annihilation vertex to be equal to the neutral kaon mass, the intersections of two track helices at the annihilation and decay vertices, respectively, and the neutral kaon momentum to be colinear with the line joining the two vertices (9 constraints for $\pi^+\pi^-$ events and 6 constraints for semileptonic events).

The offline identification of the electrons (positrons) is done with an e/π separator which consists of a neural network based on the PID information (energy loss in scintillators, number of photo-electrons per unit path length in the Čerenkov counter and time of flight).

4 Δm measurement [6]

A precision measurement of Δm is done by using the semileptonic decay channel. Assuming the $\Delta S = \Delta Q$ rule (in the Standard Model $\Delta S = -\Delta Q$ is highly suppressed), K^0 can only decay to $\pi^- e^+ \nu_e$ and $\overline{\mathrm{K}^0}$ can only decay to $\pi^+ e^- \bar{\nu}_e$. Therefore the charge of the lepton $e^{\pm}$ is a marker of the strangeness at the decay time, whereas the charge of the kaon $\mathrm{K}^{\pm}$ is a marker of the strangeness of the neutral kaon at the production time. We can define two different kinds of rates for initial K^0 and $\overline{\mathrm{K}^0}$:

$$\overline{N}^+ = R(\overline{\mathrm{K}^0}, \pi^- e^+ \nu_e, \tau), \quad N^- = R(\mathrm{K}^0, \pi^+ e^- \bar{\nu}_e, \tau), \tag{4}$$

$$\overline{N}^- = R(\overline{\mathrm{K}^0}, \pi^+ e^- \bar{\nu}_e, \tau), \quad N^+ = R(\mathrm{K}^0, \pi^- e^+ \nu_e, \tau) \,. \tag{5}$$

The first two rates (4) correspond to events with a ($\Delta S = 2$) transition whereas the rates (5) correspond to events with a ($\Delta S = 0$) transition. The rates (5) and (4) are compared by forming the asymmetry

$$A_{\Delta \mathrm{m}}(\tau) = \frac{N^+ + \overline{N}^- - (\overline{N}^+ + N^-)}{N^+ + \overline{N}^- + \overline{N}^+ + N^-}, \tag{6}$$

and the strangeness oscillation frequency is determined through the equation :

$$A_{\Delta \mathrm{m}}(\tau) = \frac{2\cos(\Delta \mathrm{m}\,\tau)\; e^{-\frac{1}{2}(\gamma_{\mathrm{S}}+\gamma_{\mathrm{L}})\tau}}{(1+Re(x))e^{-\gamma_{\mathrm{S}}\tau}+(1-Re(x))e^{-\gamma_{\mathrm{L}}\tau}} \tag{7}$$

where a possible violation of the $\Delta S = \Delta Q$ rule is taken into account by the parameter $Re(x)$. The fit of the asymmetry $A_{\Delta \mathrm{m}}(t)$ to the data leaving Δm and $Re(x)$ as free parameters (fig. 1) gives the following result :

$$\Delta \mathrm{m} = (0.5274 \pm 0.0029_{stat} + 0.0005_{sys}) \times 10^{10} \hbar s^{-1}, \tag{8}$$

and the value of $Re(x)$ is compatible with zero.

The systematic error comes mainly from the the Monte Carlo estimation of the background at short decay times.

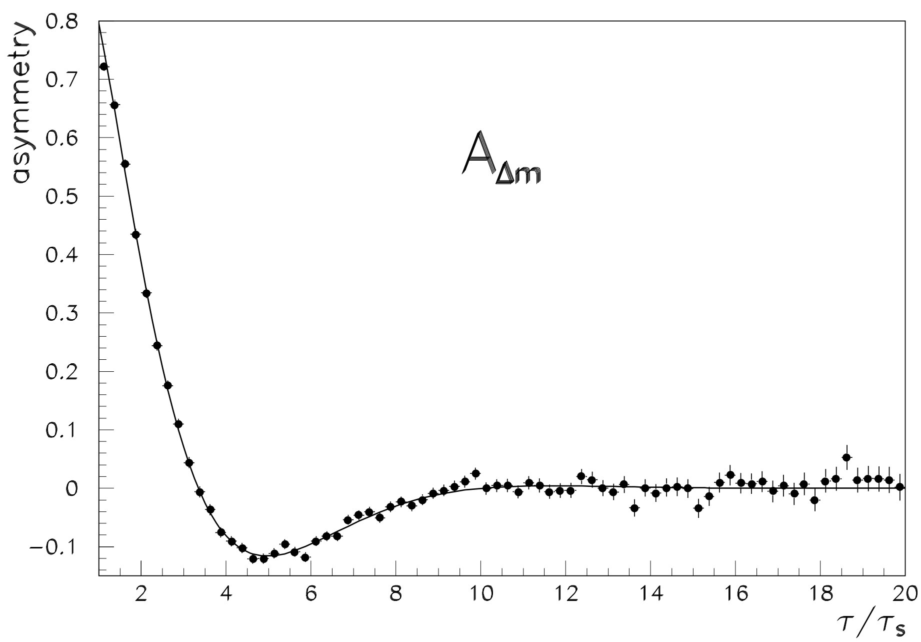

Figure 1: *The time dependent asymmetry $A_{\Delta m}$. The solid line is the result of the fit.*

5 η_{+-} measurement [7]

For the $\pi^+\pi^-$ channel, the $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ decay time distribution corrected for the acceptance is displayed in figure 2. For decay times $\tau \lesssim 10\ \tau_{\mathrm{S}}$, it is clearly dominated by two-pion decays whereas at large decay time a significant fraction of background remains, consisting mainly of semileptonic $\mathrm{K_L}$ decays. From a fit to the data, leaving the $\mathrm{K_S}$ mean life and the amount of background semileptonic decays as free parameters, the number of background events is found to be 1.05 ± 0.15 times the number of $\mathrm{K_L}$ decaying to two pions.

Even if the $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ are produced symmetrically, the number of tagged $\mathrm{K^0}$ and $\overline{\mathrm{K^0}}$ is not exactly equal. This is due to different interactions of $\mathrm{K^+}$ and $\mathrm{K^-}$ in the detector material (essentially the PID) and to geometrical imperfections of the detector. In order to cancel the geometrical biases, the magnetic field polarity is frequently reversed. The remaining difference in the tagging efficiency depends on the kinematical configuration of the primary tracks (Kπ). Hence, we correct this effect event by event by applying a weight as a function of the (Kπ) kinematical variables.

Despite the fact, that the material of the detector was minimized, the effect of coherent regeneration on the K^0 and $\overline{\mathrm{K}^0}$ rates is not negligible. In the absence of experimental data for the difference between the forward scattering amplitudes of K^0 and $\overline{\mathrm{K}^0}$ in the momentum region of the present experiment ($< 800\ \mathrm{MeV}/c$), we have used the values calculated recently by Eberhard and Uchiyama [8] in order to correct event by event for coherent regeneration.

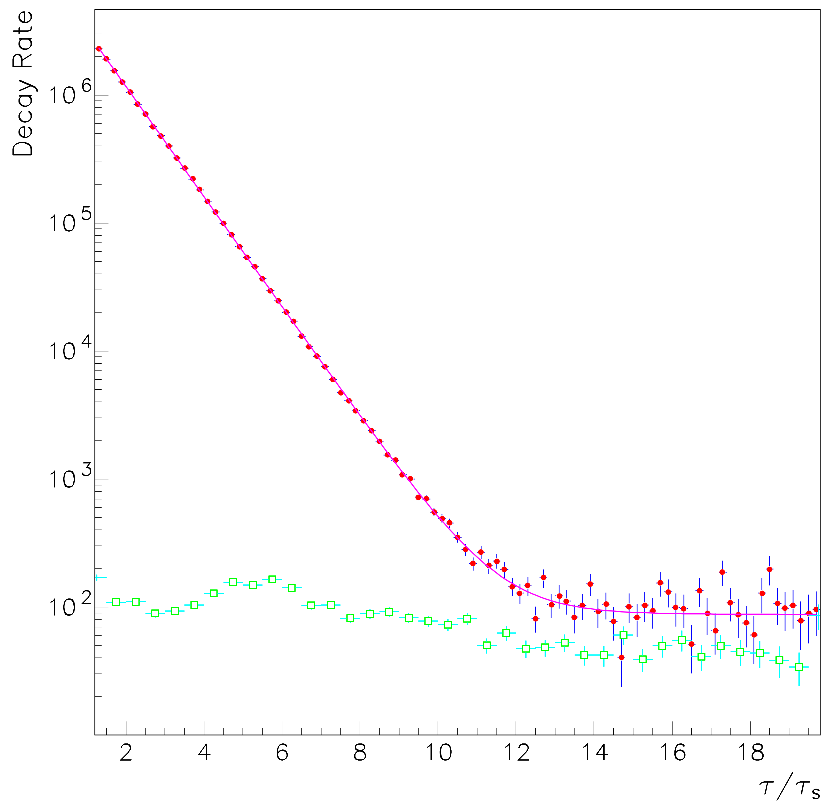

Figure 2: *Sum of* K^0 *and* $\overline{\mathrm{K}^0}$ *decay rates (normalized and corrected for* $\mathrm{K}^0 \to \pi^+\pi^-$ *acceptance) and the background contribution determined with a Monte Carlo simulation.*

After background subtraction, correction of relative tagging efficiencies and correction of regeneration the asymmetry $A_{+-}(t)$ of equation (1) is constructed from the time-dependent decay rates (see fig. 3) and fitted with equation (2) to extract $|\eta_{+-}|$, ϕ_{+-} and α.
With the Δm value (8) obtained from the semileptonic decays our results are:

$$\begin{aligned} |\eta_{+-}| &= (2.312 \pm 0.043_{\mathrm{stat.}} \pm 0.030_{\mathrm{syst.}} \pm 0.011_{\tau_S}) \times 10^{-3} \\ \phi_{+-} &= 42.7^\circ \pm 0.9^\circ_{\mathrm{stat.}} \pm 0.6^\circ_{\mathrm{syst.}} \pm 0.9^\circ_{\Delta\mathrm{m}}. \end{aligned}$$

Using the PDG [1] value of Δm, we find :

$$\begin{aligned} |\eta_{+-}| &= (2.311 \pm 0.043_{\mathrm{stat.}} \pm 0.030_{\mathrm{syst.}} \pm 0.011_{\tau_S}) \times 10^{-3} \\ \phi_{+-} &= 44.5^\circ \pm 0.9^\circ_{\mathrm{stat.}} \pm 0.6^\circ_{\mathrm{syst.}} \pm 0.8^\circ_{\Delta\mathrm{m}}. \end{aligned}$$

Our systematic errors result mainly from the present uncertainties on the regeneration and the value of Δm.

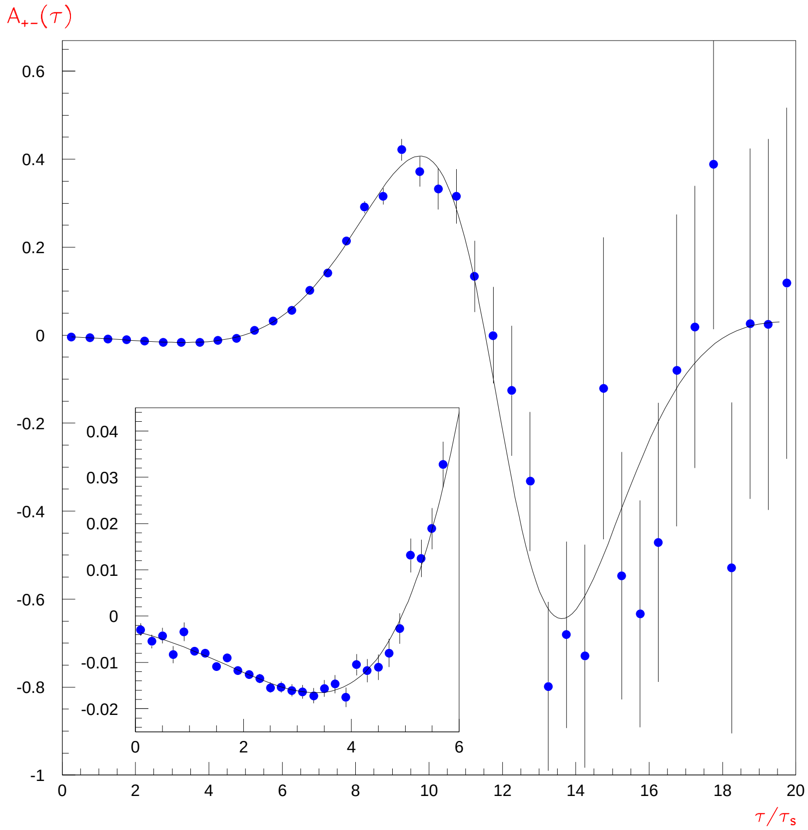

Figure 3: *Decay rate asymmetry as function of the decay time. The line is the result of our fit.*

6 Test of CPT invariance

The comparison of ϕ_{+-} with $\phi_{\rm SW} = 43.30° \pm 0.16°$ yields an indirect test of CPT invariance. Under the assumption that CPT is conserved in the decay matrix ($\Gamma_{11} = \Gamma_{22}$) and neglecting the direct CP violation, we have

$$\eta_{+-} = \varepsilon_{\rm T} + \delta_{\rm CPT} + i\phi_0 \quad (9)$$

where $\varepsilon_{\rm T}$ and $\delta_{\rm CPT}$ describe respectively (CP and T) violation and (CP and CPT) violation in the kaon mixing matrix $M - i\frac{\Gamma}{2}$. The phase of $\varepsilon_{\rm T}$ is $\phi_{\rm SW}$ and different by $\frac{\pi}{2}$ from the phase of $\delta_{\rm CPT}$.

$$\varepsilon_{\rm T} = \frac{\Delta {\rm m} \cdot \arg(-M_{12}\Gamma_{12}^*)}{\sqrt{4\Delta m^2 + \Delta\Gamma^2}} e^{i\phi_{\rm SW}} \qquad \delta_{\rm CPT} = \frac{m_{\overline{\rm K^0}} - m_{\rm K^0}}{\sqrt{4\Delta m^2 + \Delta\Gamma^2}} e^{i(\phi_{\rm SW}+\frac{\pi}{2})}$$

A limit on the $\overline{\rm K^0} - {\rm K^0}$ mass is deduced from equation (9) :

$$m_{\overline{\rm K^0}} - m_{\rm K^0} = [|\eta_{+-}|(\phi_{+-} - \phi_{\rm SW}) - \phi_0 \cos(\phi_{\rm SW})].\sqrt{4\Delta m^2 + \Delta\Gamma^2}.$$

Normally the term ϕ_0 is neglected when analysing the phase difference $\phi_{+-} - \phi_{\rm SW}$ [9]. With the CPLEAR results, we can give a strict experimental limit on this term defined as

$$\phi_0 = \frac{1}{2}(\arg(\Gamma_{12}) - \arg(a_0^* \overline{a_0})),$$

where a_0 and $\overline{a_0}$ are respectively the amplitudes for the K^0 and $\overline{\mathrm{K}^0}$ decays to $\pi\pi$ in $I = 0$. From the unitarity of the decay matrix Γ, its off-diagonal element can be written as $\Gamma_{12} = \sum_f < \mathrm{K}^0|H|f >< f|H|\overline{\mathrm{K}^0} >$ (sum over all final states $|f >$). Neglecting final states like $(\pi\pi, \mathrm{I} = 2)$, $\pi^+\pi^-\gamma$ and $\gamma\gamma$, assuming that the possible violation of the $\Delta S = \Delta Q$ rule (described by the parameter x) is identical for μ and e, and that $\eta_{+-0} = \eta_{000}$, we find:

$$\arg(\Gamma_{12}) \simeq \arg(a_0^*\overline{a_0}) + 2\frac{\gamma_\mathrm{L}}{\gamma_\mathrm{S}} \left[Br(\mathrm{K_L} \to \pi\pi\pi) Im(\eta_{+-0} - \eta_{+-}) + 4Br(\mathrm{K_L} \to l^+\pi^-\nu_l) Im(x) \right].$$

The measurements of $Im(\eta_{+-0})$ and $Im(x)$ by CPLEAR improve the estimation of ϕ_0. Using data taken between 1990 and 1993, we have $Im(\eta_{+-0}) = -16 \pm 20_{\mathrm{stat.}} \pm 8_{\mathrm{syst.}}$ and $Im(x) = 4.8 \pm 4.3_{\mathrm{stat.}} \pm 0.6_{\mathrm{syst.}}$[10]. They give $\phi_0 \cdot \cos(\phi_{\mathrm{SW}})/|\eta_{+-}| = 0.3° \pm 0.4°$ instead of $-0.2° \pm 2.9°$ with the PDG [1] values. Thus we obtain the limit :

$$\left| \frac{m_{\overline{\mathrm{K}^0}} - m_{\mathrm{K}^0}}{m_{\mathrm{K}^0}} \right| < 2.1 \cdot 10^{-18} (90\% C.L.)$$

7 Summary and prospects

We have reported the precise measurements of ϕ_{+-} and Δm performed in an independent way. The comparison of ϕ_{+-} with the superweak phase ϕ_{SW} taking into account the CPLEAR results on $Im(\eta_{+-0})$ and $Im(x)$ provides one of the most sensitive indirect tests of CPT invariance.

With additional data collected during 1994 and 1995, the statistical errors will be decreased by a factor 1.5 to 2. A dedicated measurement of regeneration parameters in 1996 will help to decrease our systematic error in ϕ_{+-} by more than a factor 2.

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