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CP VIOLATION IN THE NEUTRAL KAON SYSTEM

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CP VIOLATION IN THE NEUTRAL KAON SYSTEM

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Abstract

A short description of the K^0 system is given in order to review the known and to identify the missing observables. The review of the most recent results and of the experiments in preparation illustrates the complementarity between the classical, regenerator type, studies and the new approach using initially pure K^0 and $\bar{K}^0$ beams.

1 Introduction

Since the discovery [1] of CP violation in 1964, through the observation of the $K_L \to \pi^+\pi^-$ decay (B.R. $\sim$ 2 10^{-3}), experiments with increasing accuracy and sophistication have been devoted to the subject. Experimental evidence for CP-violation was found only in the K^0 system and until recently limited to the $K_L \to \pi^+\pi^-, \pi^0\pi^0$ channels and the charge asymmetry of semileptonic $K_L \to \pi\ell\nu$ decays, whose cosmological impact on the definition of an absolute charge should be reminded.
Although CP violation can naturally be incorporated in the standard model of the electroweak interactions based on three quark and lepton generations [2], our understanding of the transition amplitudes is limited, subject to the progress in the experimental knowledge of the Kobayashi- Maskawa mixing matrix elements and in the evaluation of the non perturbative strong interaction effects.
Basically, the nature of CP violation is not yet understood and its relevance to physics beyond the standard model is thoroughly studied [3, 4]. Interesting breakthroughs may be expected from several new, ongoing or in preparation experimental programmes :

1. the use of initially pure K^0 and $\bar{K}^0$ beams to disentangle the question whether CP violation is related only to T violation or implies violation of the CPT symmetry,
2. the extension of the experimental studies to different K_L or K_S decay channels,
3. the increase in sensitivity of future searches for so called *direct* CP violation,
4. the possibility to extend the experimental observation to the beauty sector.

Complementary studies of CP or T violation are the experiments looking for parity P or time T violation in weak interactions, i.e. the search for an Electric Dipole Moment, EDM, of the neutron and searches for Charge, C, violation in electromagnetic processes, i.e. in rare η decays. So far none of them has been observed [5]. The experimental limit on the EDM of the neutron is 1.2×10^{-25} e.cm for which a value of $\sim 10^{-30}$ e.cm is expected within the standard model. The present limit on the branching ratio of the η meson decay, $(\eta \to \pi^+\pi^-\pi^0)$ is 5×10^{-6}.
The present contribution includes a short review of the description of the K^0 system in order to identify the missing "bricks", and the review of present experiments on CP violation in the K^0 system with a brief mention of the major future studies today under preparation.
The extensions of the experimental observations to the B-sector [8, 9], the status and outlooks of the experimental information obtained from todays colliders (CESR, LEP, HERA) and progress of dedicated machine and experimental projects under preparation will not be presented here.
For completeness, the reader may refer to many recent and excellent reviews of the subject [4, 6, 7, 8].

2 Description of the K^0 system

Neutral kaons, K^0 and $\bar{K}^0$ are produced in strong interactions and are eigenstates of the strong and electromagnetic interaction but not CP eigenstates. In presence of the weak interaction, violating strangeness conservation, K^0 and $\bar{K}^0$'s can decay to non strange final states (ΔS=1) or oscillate (mix) to each other (ΔS=2).
The physical states, eigenstates of the weak interaction, the long-lived K_L and the short-lived K_S states are obtained in diagonilizing the equation [10]

$$i\frac{\partial}{\partial t}\begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix} = (M - i\frac{\Gamma}{2})\begin{pmatrix} K^0 \\ \bar{K}^0 \end{pmatrix}$$

where M the mass- and Γ the decay-matrix are 2×2 Hermitian operators.
If the weak interaction Hamiltonians are Hermitian and invariant under T, CP and CPT the matrix elements M_{ij} and Γ_{ij} must satisfy the following relations :

$| M_{12} - i\Gamma_{12}/2 | = | M_{12}^* - i\Gamma_{12}^*/2 |$ for T conservation
$| M_{12} - i\Gamma_{12}/2 | = | M_{12}^* - i\Gamma_{12}^*/2 |$ and $M_{11} = M_{22}, \Gamma_{11} = \Gamma_{22}$ for CP conservation
$M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$ for CPT conservation

CP violation can imply either T violation (no CPT violation) or CPT violation or both.
Without any assumption about CP, T or CPT, K_L and K_S are written as a function of K^0 and $\bar{K}^0$ as

$$| K_S >= \frac{1}{\sqrt{2}}[(1 + \epsilon_T + \delta_{CPT}) | K^0 > +(1 - \epsilon_T - \delta_{CPT}) | \bar{K}^0 >] \quad (1)$$
$$| K_L >= \frac{1}{\sqrt{2}}[(1 + \epsilon_T - \delta_{CPT}) | K^0 > +(1 - \epsilon_T + \delta_{CPT}) | \bar{K}^0 >]$$

where ϵ_T and δ_{CPT} depend on the eigenvalues of the effective Hamiltonian.
Adopting the phase convention[1] $\Im m(\Gamma_{12}) = 0$, the parameter ϵ_T and its phase are given by

$$\epsilon_T = \frac{< \bar{K}^0 | H_{eff} | K^0 > - < K^0 | H_{eff} | \bar{K}^0 >}{i\Delta\Gamma + 2\Delta m} \quad \text{and} \quad \varphi_{\epsilon_T} = \arg \epsilon_T = \arctan \frac{2\Delta m}{\Delta\Gamma} \simeq 44^o \quad (2)$$

where [5] $\Delta m = m_S - m_L = 2 | M_{12} | = (.5351 \pm .0024)10^{10}\hbar s^{-1}$ and $\Delta\Gamma = \Gamma_S - \Gamma_L = 2 | \Gamma_{12} | = (1.1189 \pm .0025)10^{10}s^{-1}$. The phase φ_{ϵ_T} is also known as the "superweak phase", φ_{SW}. $\epsilon_T \neq 0$ is a direct measurement of T violation (and CP violation) inducing the difference in the transition rates of $| K^0 > \rightarrow | \bar{K}^0 >$ and $| \bar{K}^0 > \rightarrow | K^0 >$.
The parameter δ_{CPT} and its phase φ_{CPT} are given by

$$\begin{aligned} \delta_{CPT} &= \frac{< \bar{K}^0 | H_{eff} | \bar{K}^0 > - < K^0 | H_{eff} | K^0 >}{i\Delta\Gamma + 2\Delta m} \\ \varphi_{CPT} &= \arg \delta_{CPT} = \varphi_{\epsilon_T} + \frac{\pi}{2} \end{aligned} \quad (3)$$

assuming CPT conservation in the decay amplitude (i.e. CPT violation only in the mass matrix). $\delta_{CPT} \neq 0$ is a direct measurement of CPT violation, implying a difference in the K^0-$\bar{K}^0$ masses, $m_{K^0} \neq m_{\bar{K}^0}$. None of these parameters has been measured directly so far. As far as the CP mixing parameter ϵ is concerned, clarifying the situation necessitates the adoption of a phase convention in the CP operation. Using the phase convention CP $| K^0 >= + | \bar{K}^0 >$ the K_L and K_S states can be written as a function of the CP eigenstates, $| K_1 >^{CP=+1} = \frac{1}{\sqrt{2}}(| K^0 > + | \bar{K}^0 >)$, $| K_2 >^{CP=-1} = \frac{1}{\sqrt{2}}(| K^0 > - | \bar{K}^0 >)$, as

$$\begin{aligned} | K_S > &= | K_1 > +\epsilon_S | K_2 > \\ | K_L > &= | K_2 > +\epsilon_L | K_1 > \end{aligned} \quad (4)$$

The parameters ϵ_S, ϵ_L represent the small "wrong" CP admixtures in the physical states K_S and K_L respectively. ϵ_S and ϵ_L can be simply related to the parameters ϵ_T (2) and δ_{CPT} (3) through

$$\epsilon_S = \epsilon_T + \delta_{CPT}$$
$$\epsilon_L = \epsilon_T - \delta_{CPT}$$

So far, only ϵ_L was measured, but ϵ_S was never measured before.
Summarizing the present information on CP, T and CPT parameters, the established facts of the $K_L \rightarrow 2\pi$ transition and the charge asymmetry δ_l in the semileptonic K_L decays prove only that K_L is not a pure CP = -1 state. They can not distinguish between the implication of the observed CP violation on T and/or CPT violation(s).
The measurement of ϵ_S, ϵ_T and in particular of δ_{CPT} could provide direct evidence for CPT violation. Such measurements can be addressed to in experiments using initially pure K^0 and $\bar{K}^0$ beams.

[1] A description without any phase convention can be found in [8]

2.1 The decays into two pion final states

The two pion final states are eigenstates of the strong and electromagnetic interaction, have a total angular momentum of $J_{2\pi} = 0$ and an isospin $I_{2\pi} = 0$ or 2 as allowed by Bose statistics.
The K^0, $\bar{K}^0$ decay amplitudes are written traditionally, assuming CPT invariance in the decay, as

$$A_{I=0,2} = a_{0,2}\, e^{i\delta_{0,2}} \quad \text{and} \quad \bar{A}_{I=0,2} = a^*_{0,2}\, e^{i(\delta_{0,2}+\theta_{CP}-\bar{\theta}_T)} \tag{5}$$

including the weak interaction amplitudes a_I and the strong interaction "$\pi\pi$" phase shifts δ_I, which are determined from "$\pi\pi$" elastic scattering at energies $\sqrt{s} = m_{K^0}$.
The CP violation parameters are expressed in terms of the K_L and K_S decay amplitudes through

$$\eta_{I=0,2} = \frac{< 2\pi(I=0,2) \mid H_{weak} \mid K_L >}{< 2\pi(I=0,2) \mid H_{weak} \mid K_S >} = -\delta_{CPT} + \epsilon_T + \frac{i}{2}(2\varphi_{0,2} + \varphi_\Gamma + \bar{\theta}_T - \theta_{CP}) \tag{6}$$

where $\varphi_\Gamma = \arg \Gamma_{12}$, with Γ_{12} the off diagonal element of the decay matrix, θ_{CP} is the "arbitrary" phase of the CP operation, $CP \mid K^0 >= e^{i\theta_{CP}} \mid \bar{K}^0 >$, θ_T is the phase of the T operation, T$\mid K^0 >= e^{i\theta_T} \mid K^0 >$and $\varphi_{0,2}$ the phases of the I=0,2 weak amplitude a_I.
The term in the parenthesis is usually considered to be zero (see below).
With our phase conventions $\Im m(\Gamma_{12}) = 0$ and $CP \mid K^0 >=\mid \bar{K}^0 >$

$$\eta_{I=0,2} = -\delta_{CPT} + \epsilon_T + i\varphi_{0,2} \tag{7}$$

The CP violation parameters measured experimentally, are

$$\begin{aligned} \eta_{+-} &= \mid \eta_{+-} \mid e^{i\varphi_{+-}} = \frac{< \pi^+\pi^- \mid H_{weak} \mid K_L >}{< \pi^+\pi^- \mid H_{weak} \mid K_S >} \simeq \eta_{I=0} + \epsilon' \\ \eta_{00} &= \mid \eta_{00} \mid e^{i\varphi_{00}} = \frac{< \pi^0\pi^0 \mid H_{weak} \mid K_L >}{< \pi^0\pi^0 \mid H_{weak} \mid K_S >} \simeq \eta_{I=0} - 2\epsilon' \end{aligned} \tag{8}$$

where $\epsilon' = \frac{i}{\sqrt{2}}\Im m(\frac{a_2}{a_0})e^{i(\delta_2-\delta_0)}$ is the parameter expressing the so called direct CP violation, i.e. CP violation in the decay amplitude (ΔS=1 transitions). Note that the phase of ϵ', $\arg \epsilon' = \frac{\pi}{2} + \delta_2 - \delta_0$ is determined by the s-wave strong $\pi\pi$ phase shifts.
In order for $\Re e(\epsilon')$ to be different from zero, $\Re e(\epsilon') \neq 0$, the strong and weak amplitude phases for I = 0 and I = 2 must be different : $\delta_2 \neq \delta_0$ and $\arg a_2 \neq \arg a_0$.
Experimentally one finds $\delta_0 - \delta_2 = 42^o \pm 4^o$ [32] and $\left|\frac{a_2}{a_0}\right| = 0.045$ [12] illustrating the I = 2 amplitude suppression by the ΔI = $\frac{1}{2}$ rule. Theoretically one expects no direct CP violation, $\epsilon' = 0$, if the violation is due only to the superweak interaction and different phases for the weak amplitudes $\arg a_2 \neq \arg a_0$, if CP violation is due to the weak interaction. Traditionally, direct CP violation is looked for experimentally in differences between the CP violation parameters η_{+-} and η_{00} (8). Because $\epsilon' \ll 1$ and its phase is close to φ_{SW}, $\arg\ \epsilon' \simeq \arg\ \epsilon_T$, one expects the phases of η_{+-} and η_{00} to be equal.

2.2 The decays into semileptonic final states

The study of the semileptonic decays of the neutral kaons is the best illustration of the potentials offered by initially pure K^0 and $\bar{K}^0$ beams in disentangling T and CPT violation associated to the existing CP violation.
Four decay amplitudes can be defined in this channel, two for K^0 and $\bar{K}^0$ decaying into $\ell^+\pi^-\nu$.

$$\begin{aligned} A_+ &= < \pi^-(\vec{p_\pi}), \ell^+(\vec{p_l}, \vec{s}), \nu(\vec{p_\nu}) \mid H_{weak} \mid K^0 > \qquad \Delta S(-1) = \Delta Q(-1) \\ \bar{A}_+ &= < \pi^-(\vec{p_\pi}), \ell^+(\vec{p_l}, \vec{s}), \nu(\vec{p_\nu}) \mid H_{weak} \mid \bar{K}^0 > \qquad \Delta S(+1) \neq \Delta Q(-1) \end{aligned}$$

and two for K^0 and $\bar{K}^0$ decays into $\ell^-\pi^+\nu^-$

$$\begin{aligned} A_- &= < \pi^+(\vec{p_\pi}), \ell^-(\vec{p_l}, -\vec{s}), \bar{\nu}(\vec{p_\nu}) \mid H_{weak} \mid K^0 > \qquad \Delta S(-1) \neq \Delta Q(+1) \\ \bar{A}_- &= < \pi^+(\vec{p_\pi}), \ell^-(\vec{p_l}, -\vec{s}), \bar{\nu}(\vec{p_\nu}) \mid H_{weak} \mid \bar{K}^0 > \qquad \Delta S(+1) = \Delta Q(+1) \end{aligned}$$

The amplitudes $\bar{A}_+$ and A_- are suppressed by the ΔS = ΔQ rule, from which a suppression of the order of $10^6 - 10^7$ is expected in the standard model.
Consequently the ΔS = ΔQ rule violation is measured experimentally by the complex parameter x, defined using the superposition of the "forbidden" amplitudes with the conjugate "allowed" ones :

$$x = \frac{\sum_{\vec{s}} \int d\Omega A_+^* \bar{A}_+}{\sum_{\vec{s}} \int d\Omega \mid A_+ \mid^2} = \frac{\sum_{\vec{s}} \int d\Omega A_- \bar{A}_-^*}{\sum_{\vec{s}} \int d\Omega \mid \bar{A}_- \mid^2} \tag{9}$$

where CPT conservation in the decay is assumed. Note that the charge asymmetry δ_l observed in the semileptonic decays can be expressed in terms of the T and CPT violation parameters (eq. 2,3) as

$$\delta_\ell = \frac{\Gamma(K_L \to \pi^-\ell^+\nu) - \Gamma(K_L \to \pi^+\ell^-\bar{\nu})}{\Gamma(K_L \to \pi^-\ell^+\nu) + \Gamma(K_L \to \pi^+\ell^-\bar{\nu})} \simeq 2\Re e(\epsilon_T) + 2\Re e(\delta_{CPT}) \tag{10}$$

and cannot be used for distinguishing T from CPT violation. Indeed, this separation requires the use of initially pure K^0 and $\bar{K}^0$ states [13]. One can then define the following appropriate decay rates :

R_+(t) : for an initial K^0 to decay into $\pi^-\ell^+\nu$ at time t
$\bar{R}_+$(t) : for an initial $\bar{K}^0$ to decay into $\pi^-\ell^+\nu$ at time t
R_-(t) : for an initial K^0 to decay into $\pi^+\ell^-\bar{\nu}$ at time t
$\bar{R}_-$(t) : for an initial $\bar{K}^0$ to decay into $\pi^+\ell^-\bar{\nu}$ at time t

and use the time development of K^0 and $\bar{K}^0$ to define the adequate *particle-antiparticle* asymmetries allowing the access directly to the CPT and T violation parameters. These are:

$$A_{CPT}(t) = \frac{\bar{R}_-(t) - R_+(t)}{\bar{R}_-(t) + R_+(t)} = \frac{4\Re e(\delta_{CPT})(e^{-\Gamma_S t} - e^{-\Gamma_L t}) - 4\Im m(2\delta_{CPT} - x)e^{-\bar{\Gamma}t}\sin(\Delta m t)}{e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-\bar{\Gamma}t}\cos(\Delta m t)} \tag{11}$$

with $\bar{\Gamma}$ the average decay width $(\Gamma_L + \Gamma_S)/2$, which for large t becomes

$$\lim_{t\to\infty} A_{CPT}(t) = 4\Re e(\delta_{CPT}) \tag{12}$$

and

$$A_T(t) = \frac{\bar{R}_+(t) - R_-(t)}{\bar{R}_+(t) + R_-(t)} = 4\Re(\epsilon_T) - \frac{4\Im m(x)e^{-\bar{\Gamma}t}\sin(\Delta m t)}{e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-\bar{\Gamma}t}\cos(\Delta m t)} \tag{13}$$

for which

$$\lim_{t\to\infty} A_T(t) = 4\Re e(\epsilon_T) \tag{14}$$

It must be noted that A_T depends only on the real part of ϵ_T if the $\Delta S = \Delta Q$ rule is valid.

2.3 The decays into $\pi^+\pi^-\pi^0$ final states

Beyond the interest in establishing CP violation in other non leptonic final states, the study of the $K^0 \to 3\pi$ decay channels offers the possibility to search for direct, $\Delta S = 1$, CP violation independently of the 2π channel. Moreover, measurements of the 3π decay amplitudes of charged or neutral kaons are an important testing ground for chiral perturbation theory models, in that they allow the study of the strong $\pi\pi$ phase shifts and meson rescattering corrections near threshold [14]. More

specifically, separating out the CP conserving, pure $\Delta I = \frac{3}{2}$, $K_S \to \pi^+\pi^-\pi^0$ amplitude from the CP violating one would give access to the I=1 and I=2 strong $\pi\pi$ phase shifts, reflected in the imaginary part of this amplitude.
Since the CP quantum number of the $\pi^+\pi^-$ state is +1, the CP value of a three pion state will depend on the relative angular momentum, $l_{\pm 0}$, between two pions and the third one, $CP_{3\pi} = (-1)^{l_{\pm 0}+1}$. Kinematic considerations are essentially limiting the possible 3π final states in K^0 decays.

a) the phase space available is relatively small ($m_{K^0} \simeq 3m_\pi$) and only $l_{\pm 0} = 0, 1$ are accessible
b) total angular momentum (l) - isospin (I) anti-symmetrisation restrains to the lowest isospin, I = 0,2 and I = 1,3, combinations for $l_{\pm 0} = 1$ and $l_{\pm 0} = 0$ respectively
c) I = 0 is "suppressed", it would require anti-symmetrization of the three pions $\pi^+\pi^-\pi^0 (\sim T_\pi^3)$
d) I = 3 is "suppressed" because of the ΔI = $\frac{1}{2}$ rule.

So, taking into account Bose statistics, phase space and total angular momentum - isospin anti-symmetrization requirements, only 2 possible observable states are left : the $CP_{3\pi}$ = -1 (l = 0, I = 1) and the $CP_{3\pi}$ = +1 (l = 1, I = 2) states.
In analogy to the 2π decay channel (5), the 3π decay amplitudes for K^0 and $\bar{K}^0$ are :

$$\begin{aligned} A(K^0 \to \pi^+\pi^-\pi^0) &= a(I=2, m_{+0}, m_{-0})e^{i\delta_{3\pi(I=2)}} + a(I=1, m_{+0}, m_{-0})e^{i\delta_{3\pi(I=1)}} \\ A(\bar{K}^0 \to \pi^+\pi^-\pi^0) &= a^*(I=2, m_{+0}, m_{-0})e^{i\delta_{3\pi(I=2)}} \\ &\quad -a^*(I=1, m_{+0}, m_{-0})e^{i\delta_{3\pi(I=1)}} \end{aligned}$$

where a, a^* are the weak decay amplitudes, m_{+0},m_{-0} are the two-pion invariant masses IM ($\pi^+\pi^0$), IM ($\pi^-\pi^0$), and δ's are the strong interaction phase shifts, expected to be small due to the small pions kinetic energies, T_π.
The weak decay amplitudes a, for I = 2, are antisymmetric in x, the Dalitz variable defined as x = $m_{\pi^+\pi^0} - m_{\pi^-\pi^0}$ and their contribution cancels out when integrating over the whole Dalitz plot x-space.
The decay amplitudes of the physical states K_S and K_L can be written as :

$$\begin{aligned} A_S^{+-0} &= A_S^{CP+1}(I=2, m_{+0}, m_{-0}) + A_S^{CP-1}(I=1, m_{+0}, m_{-0}) \\ A_L^{+-0} &= A_L^{CP+1}(I=2, m_{+0}, m_{-0}) + A_L^{CP-1}(I=1, m_{+0}, m_{-0}) \end{aligned} \tag{15}$$

In A_S^{+-0} the I = 2, CP allowed amplitude is momentum l-suppressed and the I = 1 amplitude is CP forbidden. In A_L^{+-0} the I = 2 amplitude can be neglected as being both CP- and l-suppressed. Therefore both CP-allowed and -forbidden K_S amplitudes will interfere with the CP allowed K_L amplitude. However the interference effect of the CP allowed K_S amplitude, A_S^{CP-1} will vanish if integrated over all x.
The parameter describing the CP violation in the $K_S \to 3\pi$ decay is given by :

$$\eta_{+-0} = \frac{\int_X d\Omega A_S^{CP-1}(I=1)\, A_L^{*CP-1}(I=1)}{\int_X d\Omega \left|A_L^{CP-1}(I=1)\right|^2} \simeq \delta_{CPT} + \epsilon_T + i\varphi_{3\pi}^{I=1} = \epsilon_S + i\varphi_{3\pi}^{I=1} \tag{16}$$

where the existence of $\varphi_{3\pi}^{I=1}$ is a sign for direct (ΔS = 1) CP violation in $K^0 \to \pi^+\pi^-\pi^0$ decays.
The CP allowed K_S contribution is usually measured by

$$\lambda = \frac{\int_{m_{+0}>m_{-0}} d\Omega A_S^{CP+1}(I=2, m_{+0}, m_{-0}) A^{*CP-1}_L(I=1, m_{+0}, m_{-0})}{\int_{m_{+0}>m_{-0}} d\Omega \left|A_L^{CP-1}(I=1, m_{+0}, m_{-0})\right|^2} \tag{17}$$

and can be extracted from the interferences observed in the x> $0(m_{+0} > m_{-0})$ and x< $0(m_{+0} < m_{-0})$ Dalitz plot regions separately.
From previous theoretical work [12, 15], one expects λ to be real with a magnitude of $\Re e(\lambda) \simeq 20 \times \Re e(\eta_{+-0}) \simeq 0.032$. Again it should be stressed that the $K_S - K_L$ interference is best studied using the time dependent rates asymmetries of initially pure K^0, $\bar{K}^0$ beams decaying into $\pi^+\pi^-\pi^0$.

2.4 Indirect experimental tests of CPT

In the absence of any measurements of ϵ_T and δ_{CPT}, essentially due to the lack of initially pure K^0 and $\bar{K}^0$ beams, before the LEAR facility at CERN was recognized as an intense source of tagged K^0 and $\bar{K}^0$'s, many so called indirect CPT tests have been devised [6], among which the comparison of the φ_{+-} phase with the superweak phase, φ_{SW} and the equality of the phases φ_{+-} and φ_{00}. The parameter ϵ' is small, $\epsilon' \ll 1$ and its phase close to the superweak phase $\varphi_{\epsilon'} \approx arg(\epsilon_T)$ by pure coincidence since, $\varphi_{\epsilon'}$ is given by the strong "$\pi\pi$" phase shifts, $arg(\epsilon') = \delta_2 - \delta_0 + \pi/2$, and $arg(\epsilon_t)$ by the $K_L - K_S$ mass- and decay- width differences. One then expects the phases of η_{+-} and η_{00} to be equal and $\epsilon'_\perp = \frac{1}{3} \mid \eta_{+-} \mid \tan(\varphi_{+-} - \varphi_{00})$ to be zero if CPT is conserved in the weak interaction (see fig. 1). The equality $\varphi_{+-} = \varphi_{00}$ is often considered to be an indirect test of CPT violation in the 2π decay amplitude, however this is a sensible CPT test only if ϵ' is different from zero.
The use of the phase difference $\varphi_{+-} - \varphi_{SW}$ as an indirect CPT test will be further discussed here since it is the base of the highest precision CPT test, obtained, on the equality of the masses of particles and anti-particles, in the K^0 sector [5]. As we have seen in section 2.1, the experimentally measured CP

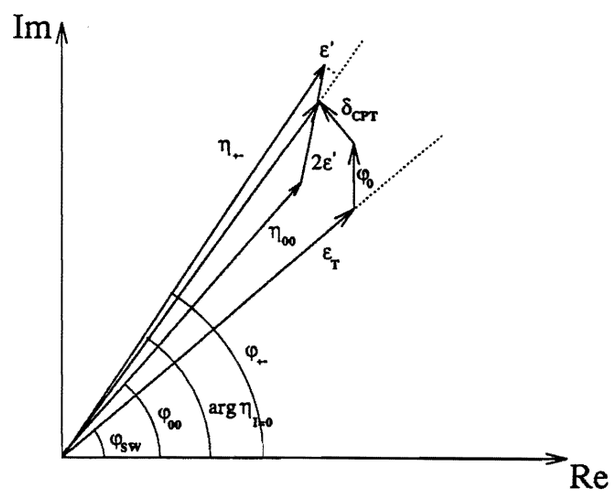


Figure 1: CP and CPT violation parameters in the K^0 system

violation parameter η_{+-}, in the absence of direct CP violation, $\epsilon' = 0$, is given by Eqs. (6) (7 and (8) with our phase conventions

$$\eta_{+-} \approx \eta_{+-}^{I=0} = -\delta_{CPT} + \epsilon_T + i\varphi_0 \tag{18}$$

where φ_0 is usually considered to be zero. Actually its predicted value within the standard model is $\mathcal{O}(10^{-7})$. Then by noting that $arg(\delta_{CPT}) = \varphi_{SW} + \frac{\pi}{2}$ the equality of the phases of η_{+-} and of ϵ_T can be regarded as an indirect CPT invariance test:

$$arg(\eta_{+-}) = \varphi_{+-} = arg(\eta_{I=0}) \approx arg(\epsilon_T) = \varphi_{SW}$$

The imaginary part of the weak amplitude $a_{I=0}, \varphi_0$, with our phase convention $\Im m \Gamma_{12} = 0$, is strongly dependent on the contributions of all common final states between $\bar{K}^0$ and K^0, since Γ_{12} (see eq. (6)) is summed over all real final states common to $\bar{K}^0$ and K^0. An empirical expression for φ_0 has been established [16, 8]

$$\varphi_0 = \frac{\Gamma_L}{\Gamma_S}[4.BR(K_L \to \ell^+\pi^-\nu)\Im m(x) - BR(K_L \to 3\pi)\Im m(\eta_{I=0} - \eta_{3\pi})] \tag{19}$$

as a function of experimentally well known parameters and those not yet established, i.e. the parameter x describing the $\Delta S = \Delta Q$ rule violation (9) and the CP violation parameter $\eta_{3\pi}$ (16). Using the presently available data for $\Im m(x) = -.003 \pm .026$ [5] and $\Im m(\eta_{3\pi}) = .02 \pm .12$ [17], we find that the imaginary part of $\eta_{I=0}$ can differ from $\Im m(\epsilon_T)$ by up to 1.5 10^{-4}. This translates itself into $\leq 2.7^o$ uncertainty in the phase of $\eta_{I=0}$. Clearly, with increasing precision in the φ_{+-} and in the Δm determinations, more accurate measurements of $\Im m(x)$ and $\Im m(\eta_{3\pi})$ are needed in order to use the $\varphi_{+-} - \varphi_{SW}$ comparison, on a purely experimental ground, as a CPT invariance test (see further below the CPLEAR and E621 experiments).

3 Experiments on CP violation

The review presented here will include only recent and ongoing experiments addressing todays important issues on CP violation in the neutral kaon system.

3.1 The search for direct CP violation

Direct CP violation should manifest itself in a difference between the CP violation parameters $\eta_{+-} \neq \eta_{00}$ (8), from which $\Re e(\epsilon'/\epsilon)$ can be directly deduced according to

$$\Re e\left(\frac{\epsilon'}{\epsilon}\right) \approx \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right) \tag{20}$$

The two by far most elaborate and precise experiments devoted to this search are the NA31 experiment [18] at CERN and the E731 experiment [19] at Fermilab.
Both collaborations measured double rates ratios

$$R = \left(\frac{L_{00}/S_{00}}{L_{+-}/S_{+-}}\right)_{\text{E731}} = \left(\frac{L_{00}/L_{+-}}{S_{00}/S_{+-}}\right)_{\text{NA31}} = 1 - 6\Re e\left(\frac{\epsilon'}{\epsilon}\right) \tag{21}$$

where L,S, stand for the K_L and K_S rates into two pions. The measurement of the double ratio R minimizes systematic errors due to a) differences in the K_L and K_S decay products acceptances b) detector efficiencies, electronics stability with time, deadtime, accidentals c) background effects.
E731 used a double neutral kaon beam and measured simultaneously K_L and K_S decays to $\pi^+\pi^-$ and to $\pi^0\pi^0$, using a magnetic spectrometer, a photon converter and a lead glass calorimeter, but two different triggers. As a result most of the corrections due to the detector behaviour (b) cancel out in R. The acceptances for $\pi^+\pi^-$ and $\pi^0\pi^0$ were determined using Monte Carlo simulations, including $K_L \to \pi\ell\nu$ and $K_L \to 3\pi^0$ accepted by the "$\pi^+\pi^-$" trigger and the "$\pi^0\pi^0$" trigger respectively.
NA31 used alternatively K_S and K_L beams but simultaneous detection of the $\pi^+\pi^-$ and $\pi^0\pi^0$ decays. The detection was based on pure calorimetry and charged particles tracking without magnetic field. K_S were generated using a moving regenerator along a 50m long path in order to closely match the K_S acceptance to the K_L one. Using the proton beam tuning the resulting K_S and K_L beams had very similar momentum spectra and intensities. As a result, systematic errors due to geometrical acceptance effects (a) for K_S and K_L and deadtimes as well as accidentals (b) are minimized.

Table 1 summarizes final event statistics and background levels for the two experiments. NA31 has definitely higher statistics and lower background contributions than E731, although both have non negligible background levels for the K_L neutral decay channel. NA31 established the first evidence [20] at the 3σ level for $\Re e(\epsilon'/\epsilon) \neq 0$. The final result of the collaboration is [18]

$$\Re e\left(\frac{\epsilon'}{\epsilon}\right) = (2.3 \pm .42_{stat} \pm .50_{syst})10^{-3} = (2.3 \pm .65)10^{-3}$$

channel	E731	BKG[%]	NA31	BKG[%]
$K_L \to \pi^+\pi^-$	327006	0.71	847000	0.63
$K_S \to \pi^+\pi^-$	1060687	0.204	319000	0.03
$K_L \to \pi^0\pi^0$	410043	5.16	1322000	2.67
$K_S \to \pi^0\pi^0$	800037	2.843	3241000	0.07

Table 1: Statistics (background subtracted) for E731 and NA31

where the total error includes a systematic part of 5×10^{-4} (see Table 2). It represents $\geq 3\sigma$ evidence for direct CP violation at the 10^{-3} level.
On the other hand, the Fermilab experiment finds [19]

$$\Re e\left(\frac{\epsilon'}{\epsilon}\right) = (7.4 \pm 5.2_{stat} \pm 2.9_{syst})10^{-4} = (7.4 \pm 6.0)10^{-4}$$

with a total systematic error of 2.9 $\times 10^{-4}$ (see Table 2), i.e no evidence for $\Re e(\epsilon'/\epsilon) \neq 0$ at the 10^{-3} level. Statistically the two results are compatible, within about 4%. Consequently within the present experimental precision, $\mathcal{O}(10^{-3})$, direct CP violation is not established and higher sensitivity experiments are needed. Taken from the two experiments separately or combined to $\Re e(\epsilon'/\epsilon) = 14.6 \pm 7.8 \times 10^{-4}$, the experimental uncertainty is on the high side of present theoretical expectations on ϵ'/ϵ within the Standard Model [6].

$\delta(\epsilon'/\epsilon)$ **systematics** $[10^{-4}]$	E731	NA31
acceptance	1.19	1.67
E calibration	1.60	2.17
accidentals	1.07	2.33
$3\pi^0$ bkg.	0.60	2.17
charged bkg.	0.29	1.67
trigger	1.22	1.50
regenerator diff.	0.98	-
beam scatt.	0.30	-
wire chamber ineff.	-	1.67
Total	2.9	5.0

Table 2: Systematics on $\Re e(\epsilon'/\epsilon)[10^{-4}]$

Two next generation experiments are in preparation, dedicated to the measurement of $\Re e(\epsilon'/\epsilon)$ and both aiming at precisions of $\mathcal{O}(10^{-4})$: the NA48 experiment [21] at CERN and the E832 (KTEV) experiment [22] at Fermilab.
NA48/CERN will include magnetic analysis for the $\pi^+\pi^-$ channel, an improved electromagnetic calorimeter (liq. Krypton) and the detection of all four decay modes simultaneously using two targets and two triggers for the charged and neutral mode. E832 (KTEV)/FNAL also includes magnetic analysis for the $\pi^+\pi^-$ channel, an improved electromagnetic calorimeter (CsI with high granularity) and the simultaneous detection of all four decay modes using two beams and an improved (active) regenerator.
Both experiments will use higher intensity beams and improved trigger and data acquisition systems to sensibly improve their statistics. Both experiments will benefit from the higher energy-resolution and background rejection of their detector in order to reduce the systematics sources (see table 2)

below 10^{-4}. Both experiments are expected to start taking data in late 1996.
Besides these two dedicated experiments, using high energy neutral kaon beams, the ϕ meson factory, DAΦNE, under construction in Frascati should offer excellent conditions for the study of a broad field of neutral kaon physics [23] including the high precision measurement of ϵ'/ϵ using the KLOE detector. Precisions $\delta(\Re e(\epsilon'/\epsilon))\mathcal{O}(10^{-4})$ could be reached if integrating the design high luminosity of $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$ over a couple of years. DAΦNE is expected to run late 1996.

3.2 Study of CP, T and CPT violation using initially pure K^0 and $\bar{K}^0$ beams

This was made possible for the first time at the Low Energy Antiproton Ring facility at CERN, representing a strong source of tagged K^0 and $\bar{K}^0$ (several 10^7 per day) [24]. The CPLEAR experiment [25] is essentially measuring $\bar{K}^0 - K^0$ decay rate asymmetries as a function of eigentime, from 0 to $\approx 20\ \tau_s$. Such asymmetries

$$A_f(t) = \frac{R(\bar{K}^0_{t=0} \to f)(t) - R(K^0_{t=0} \to f)(t)}{R(\bar{K}^0_{t=0} \to f)(t) + R(K^0_{t=0} \to f)(t)} \tag{22}$$

where the rates for a given final state "f" can be written as

$$R(K^0, \bar{K}^0) \propto \left|A^f_S\right|^2 e^{-\Gamma_S t} + \left|A^f_L\right|^2 e^{-\Gamma_L t} \pm 2\left|A^f_S\right|\left|A^f_L\right| e^{-\frac{\Gamma_S+\Gamma_L}{2}t} \cos(\Delta m t - \varphi^f_{S,L})$$

allow the access to the absolute value and phase of the violation parameters. Particle-Antiparticle asymmetries are an unambiguous sign of CP violation in non leptonic final states [26].
The method can be applied to several final states, even if they are not pure, CP states, e.g. the $\pi^+\pi^-\pi^0$ state. The experimental programme of CPLEAR includes : the determination of $\mid \eta_{+-} \mid, \varphi_{+-}$ in the 2π channel and the study of the CP violating and CP conserving K_S amplitudes in the 3π channel.
The initial K^0 and $\bar{K}^0$ tagging enables for the first time the direct searches for T and CPT violation, in studying the semileptonic decay channel. More specifically the measurements of ϵ_T, δ_{CPT} and $\Re e(\epsilon_S)$ as well as of Δm and x, the ΔS = ΔQ rule violation parameter, are another important part of the CPLEAR programme.

The CPLEAR method

a) K^0's and $\bar{K}^0$'s are produced in the annihilation at rest of 200 MeV/c antiprotons, delivered by LEAR ($\sim 10^6 \bar{p} s^{-1}$), in a high pressure 15-30 atm hydrogen target through the reaction $\bar{p}p \to K^\pm \pi^\mp K^0(\bar{K}^0)$ whose branching ratio is $\sim 4 \times 10^{-3}$.
b) the strangeness tagging is performed in essence in detecting the accompanying charged kaons. A multilevel intelligent fast trigger performs a total rate rejection of $\sim 10^3$ in about $30\mu s$ and selects K^0 and $\bar{K}^0$ candidate events for data acquisition, using particle identification, tracking and full kinematic reconstruction.
c) the identical $K^0, \bar{K}^0$ momentum spectra and final state (decay products) detection for K^0 and $\bar{K}^0$ minimize considerably systematic errors and reduce them below the statistical ones.

Differences in K^- and K^+ detection due to their different interaction cross sections introduce a "strangeness" tagging normalization $N_{\bar{K}^0}/N_{K^0}$ which must be measured with an accuracy of $\mathcal{O}(10^{-3})$.The detectors "residual" Charge-Parity asymmetry is measured and corrected for using data taking with alternating the sign of the magnetic field.
Fig. 2-a shows the CPLEAR detector whose fiducial volume allows tracking and observation of the $K_L - K_S$ interference from 0 to approximately $20\tau_s$, i.e. before the K_S disappears. As a counter part the experiment needs high statistics, over $10^8 K^0$ and $\bar{K}^0$ decays.

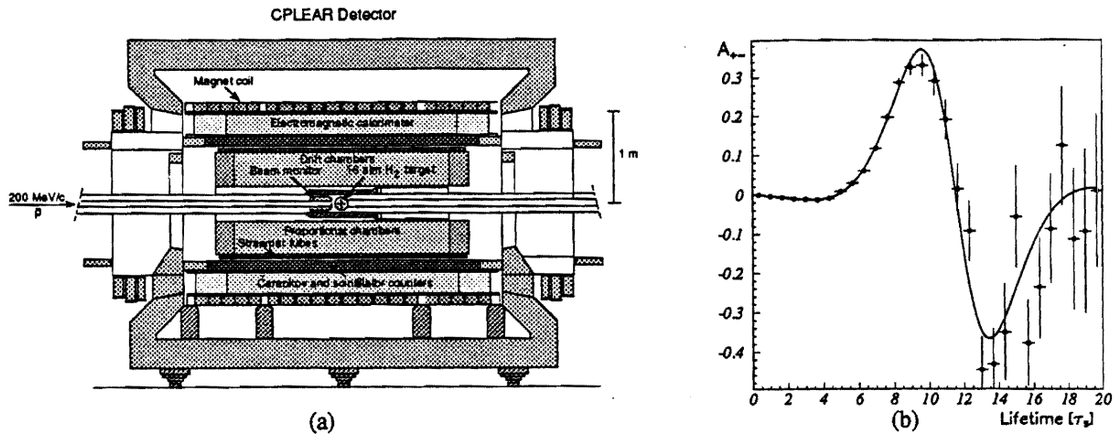


Figure 2: (a) CPLEAR detector longitudinal view (b) $\bar{K}^0$-K^0 time dependent rate asymmetry $A_{+-}(t)$, in the $\pi^+\pi^-$ channel

For concision only a few particularly illustrative results of the CPLEAR experiment will be discussed; table 3 summarizes the results obtained on several CP, T and CPT parameters, including data up to 1993 [27].

Fig. 2-b shows the $\bar{K}^0 - K^0$ asymmetry A_{+-}(t) (22). Fitting this asymmetry with its analytic expression of the physics parameters

$$A_{+-}(t) = 2\Re e(\epsilon_L) - \frac{2 \mid \eta_{+-} \mid e^{\frac{1}{2}(\Gamma_S - \Gamma_L)t}}{1 + \mid \eta_{+-} \mid^2 e^{(\Gamma_S - \Gamma_L)t}} \cos(\Delta m t - \varphi_{+-})$$

the CP violation amplitude $\mid \eta_{+-} \mid$ and phase φ_{+-} are obtained:

$$\mid \eta_{+-} \mid = (2.163 \pm .045_{stat} \pm .064_{syst} \pm .010_{\Delta m})10^{-3}$$
$$\varphi_{+-} = 44.7^o \pm .9^o_{stat} \pm 1.1^o_{syst} \pm .7^o_{\Delta m}$$

using the world average value for the $K_S - K_L$ mass difference [5]. In the future, this uncertainty will be reduced by the Δm determination from the semileptonic decay asymmetries. In particular, the precision on the phase φ_{+-} is already comparable to the world averaged one and to the precision obtained lately by the E731 and E773 collaborations [29, 31]. The expected final systematic precisions, improving with increasing statistics, are below 0.5° in φ_{+-}, not including the contribution of the Δm uncertainty, and about $\pm 0.02\ 10^{-3}$ for $\mid \eta_{+-} \mid$. Fig. 3 shows the rate asymmetry in the semileptonic channel relevant to the Δm and $\Re e(x)$ parameters. Fitting this asymmetry with its analytic expression

$$A_1(t) = \frac{(\bar{R}_-(t) + R_+(t)) - (\bar{R}_+(t) + R_-(t))}{(\bar{R}_-(t) + R_+(t)) + (\bar{R}_+(t) + R_-(t))} = \frac{2e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \cos(\Delta m t)}{(1 + 2\Re e(x))e^{-\Gamma_S t} + (1 - 2\Re e(x))e^{-\Gamma_L t}}$$

the following values were obtained for Δm and $\Re e(x)$

$$\Delta m = (.5347 \pm .0032_{stat} \pm .0009_{syst} \pm .003_{MC})10^{10}\hbar s^{-1}$$
$$\Re e(x) = (4.3 \pm 7.6_{stat} \pm 4.0_{syst} \pm 8.0_{MC})10^{-3}$$

Present CPLEAR precisions are approaching the world average one for Δm, $\Delta m = (.5351 \pm .0024)\ 10^{10}\hbar s^{-1}$, and improve the $\Re e(x)$ limit, $\Re e(x) = (6 \pm 18)\ 10^{-3}$ [5]. The importance of the

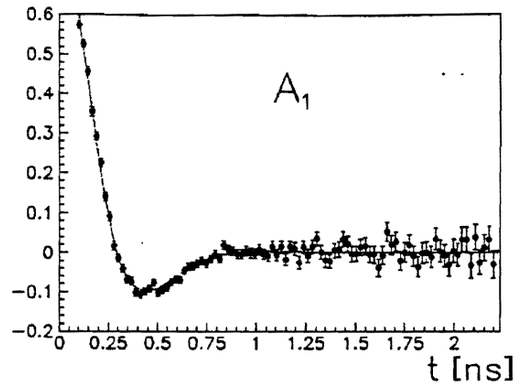


Figure 3: $\bar{K}^0$-K^0 time dependent rate asymmetry, $A_1(t)$, in the $\pi\ell\nu$ channel.

Δm determination in a decay channel independent of the 2π channel must be stressed, in contrast to the classical regenerator experiments limited to the latter channel, where the Δm determination is correlated to the phase value φ_{+-}.
From the asymmetries dedicated to the measurement of $\Re e(\epsilon_T)$ (13) and $\Re e(\delta_{CPT})$ (11), the values

$$\begin{aligned} \Re e(\epsilon_T) &= (1.2 \pm .5_{stat} \pm .5_{syst} \pm .4_{MC}) \times 10^{-3} \\ \Re e(\delta_{CPT}) &= (-0.1 \pm .5_{stat} \pm .5_{syst} \pm 0.4_{MC}) \times 10^{-3} \end{aligned}$$

were measured for the first time. The measured $\Re e(\epsilon_T)$ value is in agreement with the value expected if CPT is conserved, $\Re e(\epsilon_T) \approx 1.6\ 10^{-3}$ The main systematic uncertainties arise from the different acceptances for $\pi^+e^-\bar{\nu}$ and $\pi^-e^+\nu$ final states and will be further reduced with increasing simulation and calibration data statistics. The statistical uncertainties are expected to be improved by a factor of 2 with the final statistics including 1995. Undoubtedly these measurements would be a new and unique source of experimental information on the T and CPT violation.

Fig. 4a shows the A_{+-0}(t) asymmetry (22) of $\bar{K}^0$ and K^0 rates into the $\pi^+\pi^-\pi^0$ channel for events integrated over the whole Dalitz parameter, x, space. Fitting the data with the analytic expression:

$$\begin{aligned} A_{+-0}(t) &= \frac{\bar{R}_{\pi^+\pi^-\pi^0}(t) - R_{\pi^+\pi^-\pi^0}(t)}{\bar{R}_{\pi^+\pi^-\pi^0}(t) + R_{\pi^+\pi^-\pi^0}(t)} \\ &\approx 2\Re e(\epsilon_S) - 2\left(\Re e(\eta_{+-0})\cos(\Delta m t) + \Im m(\eta_{+-0})\sin(\Delta m t)\right) e^{-\frac{\Delta\Gamma t}{2}} \end{aligned}$$

the following values have been obtained

$$\begin{aligned} \Re e(\eta_{+-0}) &= (5 \pm 22_{stat} \pm 7_{syst})10^{-3} \\ \Im m(\eta_{+-0}) &= (16 \pm 24_{stat} \pm 18_{syst})10^{-3} \end{aligned}$$

The results have already a statistical precision an order of magnitude better than the world limits [5] $\mid \eta_{+-0} \mid^2 < .12$ (90% CL). Fixing the real part to its expected value of $\Re e(\eta_{+-0}) = \Re e(\eta_{+-}) = 1.6 \times 10^{-3}$, assuming CPT conservation and $\epsilon' = 0$, equations (7) and (15), changes the above result for the imaginary part to $\Im m(\eta_{+-0}) = .005 \pm .015$.
The CP conserving amplitude (I = 2) could affect systematically the determination of $\Re e(\eta_{+-0})$, if the detector acceptance is not symmetric in x. Studying the CPLEAR detector acceptance as a function of x, no such asymmetry has been found and the estimated upper limit on it affecting the $\Re e(\eta_{+-0})$ amplitude is less than 8% of the measured value of $\Re e(\eta_{+-0})$.

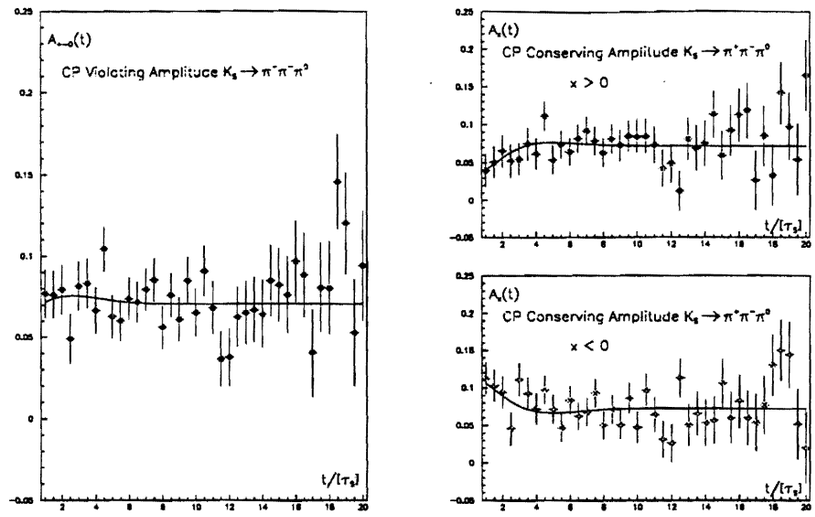


Figure 4: a) $\bar{K}^0$-K^0 time dependent rate asymmetry, $A_{+-0}(t)$, in the $\pi^+\pi^-\pi^0$ channel, b) rate asymmetries for $x > 0$ and for $x < 0$, in the $\pi^+\pi^-\pi^0$ channel.

As far as the $\Im m(\eta_{+-0})$ part is concerned present and expected final CPLEAR precisions are far from the accuracies needed in order to identify a possible direct CP violation in this channel.
The extraction of the CP conserving K_S amplitude is obtained in CPLEAR from the comparison of the A_{+-0}(t) asymmetries measured for x> 0 and x< 0 respectively:

$$\begin{aligned} A^{x\gtrless 0}_{+-0}(t) &= \frac{\bar{R}_{\pi^+\pi^-\pi^0}(t,\ x\gtrless 0) - R_{\pi^+\pi^-\pi^0}(t, x\gtrless 0)}{\bar{R}_{\pi^+\pi^-\pi^0}(t, x\gtrless 0) + R_{\pi^+\pi^-\pi^0}(t, x\gtrless 0)} \\ &\simeq 2\Re e(\epsilon_S) - 2e^{-\frac{\Delta\Gamma}{2}t}\{(\Re e(\eta_{+-0}) \pm \lambda)\cos(\Delta m t) + \Im m(\eta_{+-0})\sin(\Delta m t)\} \end{aligned} \tag{23}$$

Fig. 4b shows the two asymmetries from which the parameter λ (Eq. 17), the ratio of the CP allowed $A^{CP=+1}_{K_S}(I=2)$ amplitude to the $A^{CP=-1}_{K_L}(I=1)$ CP allowed amplitude, can be extracted: $\lambda = .051 \pm .016_{stat} \pm .020_{syst}$.
Fitting the asymmetries with both $\Re e(\lambda)$ and $\Im m(\lambda)$ free, lead to the values $\Re e(\lambda) = .047 \pm .021$ and $\Im m(\lambda) = .014 \pm .020$, thus fixing the present upper limit for $\Im m(\lambda)$ to be less than .047 (90% CL). This is the first observation of the $K_S \to 3\pi$ CP allowed amplitude and the result is in agreement with the theoretical expectation of $\Re e(\lambda) \simeq 20.\Re e(\eta_{2\pi}) = .032$.
The above value of λ allows the determination of the branching ratio of the CP allowed $K_S \to \pi^+\pi^-\pi^0$ transition : $BR(K_S \to \pi^+\pi^-\pi^0, CP = +1) = (8.2^{+6.0}_{-4.4 stat}{}^{+7.7}_{-5.2 syst})\ 10^{-7}$.
This preliminary result is in agreement with theoretical predictions. Evaluating the NLO corrections to the $K \to 2\pi$ and $K \to 3\pi$ decays in chiral perturbation theory, the determination of the different isospin amplitudes in several decay channels lead to a branching ratio of $(2.4 \pm .7\ 10^{-7})$ [15]. Alternatively, correcting the current-algebra analysis of the $\Delta I = \frac{1}{2}$ and $\Delta I = \frac{3}{2}$ amplitudes, using large N_c higher-order effective chiral lagrangians, a value of 3.9 10^{-7} was obtained [28].
Systematic errors in the CP conserving and CP violating parameters in the 3π channel are, at the present statistical level, dominated by the uncertainties in the background sources. Preliminary estimates show that they will be well below the statistical uncertainties.
Table 3 summarizes the present results and precisions on several CP,T and CPT violation parameters measured by CPLEAR, compared, where possible, to present best world values [5]. Statistical uncertainties should be reduced by a factor of two end 1995.

parameter	CPLEAR'93	PDG'92
$\mid \eta_{+-} \mid [10^{-3}]$	$2.163 \pm .045_{stat} \pm .064_{syst} \pm .010_{\Delta m}$	.023
$\varphi_{+-}[^{o}]$	$44.7 \pm .9_{stat} \pm 1.1_{syst} \pm .7_{\Delta m}$	1.2
$\Re e(\eta_{+-0})[10^{-3}]$	$5 \pm 22_{stat} \pm 7_{syst}$	170
$\Im m(\eta_{+-0})[10^{-3}]$	$16 \pm 24_{stat} \pm 18_{syst}$	210
λ	$.051 \pm .016_{stat} \pm .026_{syst}$	-
$BR(K_S \to \pi^+\pi^-\pi^0, CP = +1)[10^{-7}]$	$8.2^{+6.0}_{-4.4 stat}{}^{+7.7}_{-5.2 syst}$	-
$\Delta m[10^{10}\hbar s^{-1}]$	$.5347 \pm .0032_{stat} \pm .0009_{syst} \pm .003_{MC}$	.0024
$\Re e(x)[10^{-3}]$	$4.3 \pm 7.6_{stat} \pm 4.0_{syst} \pm 8.0_{MC}$	18
$\Im m(x)[10^{-3}]$	$10.1 \pm 4.1_{stat} \pm 1.3_{syst} \pm 5.0_{MC}$	26
$\Re(\epsilon_S)[10^{-3}]$	$0.9 \pm .7_{stat} \pm .3_{syst} \pm .7_{MC}$	-
$\Re e(\epsilon_T)[10^{-3}]$	$1.1 \pm .5_{stat} \pm .5_{syst} \pm .4_{MC}$	-
$\Re e(\delta_{CPT})[10^{-3}]$	$-.1 \pm .5_{stat} \pm .5_{syst} \pm .4_{MC}$	-

Table 3: Present results of the CPLEAR experiment and PDG'92 precisions

3.3 The E621 Experiment at Fermilab

The experiment was designed to study CP-violation in the $K_S \to \pi^+\pi^-\pi^0$ decay channel using $K_L K_S$ interference [30]. Fig. 5-a shows the double kaon beam scheme where one kaon beam is produced $\approx$ 27 m upstream of the main "interference" target and is used for normalization and the second one at the front of the decay volume under study, of about $3\tau_S$.
Events from the "interference" target include both K_S and K_L events, whereas those originating from the "normalization" target are mostly K_L. The eigentime regions covered by the events originating from the two targets are of comparable size and cover altogether an eigentime region comprised between 0.6 and 7.6 τ_S. Fig. 5-b shows the general layout of the experiment. The detector includes a magnetic spectrometer for the charged decay products π^+, π^- and a lead glass $(12X_0)$ electromagnetic calorimeter for neutrals detection.

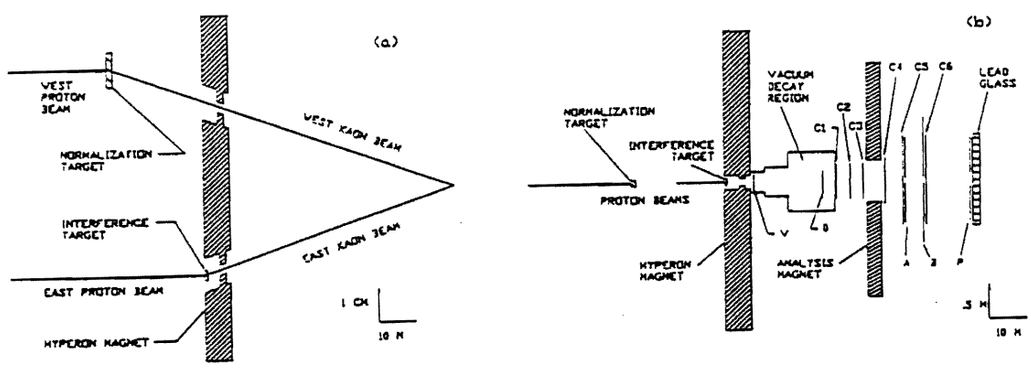


Figure 5: E621 experimental layout

The event selection criteria include the kinematic conditions $IM(\gamma\gamma) \leq m_{\pi^0} + 3\sigma, IM(\pi^+\pi^-\gamma\gamma) \leq m_{K^0} + 3\sigma$ and $IM(e^+e^-) > .085 GeV/c^2$ in order to eliminate the Dalitz decays, $\pi^0 \to e^+e^-\gamma$.
Backgrounds come essentially from production in the collimators, $\sim$ 6% at 120 GeV/c and $\sim$ 1% at 360 Gev/c, as well as γ conversion in the spectrometer, $\sim$ 13%.
$272000\pi^+\pi^-\pi^0$ and $541000\pi^+\pi^-$ reconstructed events were obtained this way, binned in momentum and decay time [p,t] and fitted by the function $T(p,t) = N_L^0(p) f(t) A(p,t)$, where $N_L^0(p)$ is the K_L

spectrum at t=0, $f(t)$ is the decay probability given by the integration of the decay time distribution over the [p,t] interval and $A(p,t)$ is the detector acceptance determined by Monte-Carlo simulation. From the fit the CP violation parameters

$$\begin{aligned} \Re e(\eta_{+-0}) &= .019 \pm .027 \\ \Im m(\eta_{+-0}) &= .019 \pm .061 \end{aligned} \tag{24}$$

were obtained. Using the constraint that $\Re e(\eta_{+-0}) = \Re e(\eta_{+-}) = .0016$, the imaginary part of η_{+-0} changes to $\Im m(\eta_{+-0}) = -.015 \pm .017 \pm .025$.
Systematic uncertainties come essentially from the uncertainty in the K_L/K_S normalization. This result is of comparable precision to the CPLEAR result as far as the statistics is concerned but its systematic uncertainty is larger.
The overall precision in this channel is improved by an order of magnitude over previous results [5], but none of the present generation experiments will attend the precision level required for establishing the corresponding CP violation parameter, expected to be $\mid \eta_{+-0} \mid \sim 2 \times 10^{-3}$.

3.4 Indirect CPT tests

As already mentioned (see 2.4) recent measurements of $\Im m(x)$ by CPLEAR and $\Im m(\eta_{3\pi})$ by CPLEAR and E621 should greatly improve the validity of the φ_{+-} and φ_{SW} comparison as an indirect CPT test. Using the recent results for $\Im m(x)$

$$\begin{aligned} \Im m(x) &= (10.1 \pm 4.1_{stat} \pm 1.3_{syst} \pm 5.0_{MC})10^{-3} \ (CPLEAR) \\ \Im m(\eta_{+-0}) &= (16 \pm 24_{stat} \pm 18_{syst})10^{-3} \ (CPLEAR) \\ &= (19 \pm 61)10^{-3} \ (E621) \end{aligned} \tag{25}$$

and equation 19, one obtains $\approx 6.4\ 10^{-5}$ for the contribution of φ_0 to $\Im m(\epsilon_T)$. This implies a $\leq 1.2^o$ uncertainty in the phase of $\eta_{I=0}$ and represents an improvement of a factor ≈ 2.5. The above contribution of 1.2^o in $arg(\eta_{I=0})$ can be expressed in terms of the well known CPT test in the K^0 sector as a contribution of

$$\frac{\mid m_{\bar{K}^0} - m_{K^0} \mid}{< m_{K^0} >} \leq 10^{-18}$$

This is to be compared to the value of $\leq 4\ 10^{-18}$ (90% C.L.), given as an upper limit for CPT violation in the mass matrix, using the best 1992 values of the CP violation parameters [5].
With the experimental precisions expected to be improved by a factor of ≈ 2 with full CPLEAR statistics, the uncertainty in the phase of $\eta_{I=0}$ should be reduced to $< 0.6^o$.

With the best values [5] of Δm, τ_S and φ_{+-} one obtains for the phase of ϵ_T, $\varphi_{SW} = 43.7^o \pm .2^o$ and the difference $\varphi_{+-} - \varphi_{SW} = 2.9^o \pm 1.2^o$, which can be seen as a 2.4σ effect of possible CPT violation. Recently [29], the E731 collaboration published a detailed study of all experimental data in the 2π channel from which a more consistent set of values for the neutral kaon parameters Δm, τ_S, $\varphi_{00} - \varphi_{+-}$ and φ_{+-} has been deduced. K_L data from the event populations originating upstream and downstream of their regenerator have been binned as a function of momentum p and decay length z, and fitted using the appropriate analytic functions [29]. Fits under different conditions have then been performed, the results of which are summarized in Table 4.

a) with the phases fixed as $\varphi_{+-} = \varphi_{00} = \varphi_{SW}$, the CP violation amplitudes η_{+-}, η_{00} taken from [5] and letting the regeneration amplitude parameters, as well as the K_S lifetime and the $K_S - K_L$ mass difference free : the obtained lifetime τ_S is in excellent agreement with, but the $K_S - K_L$ mass difference is found 2.2 σ below, the best world values [5].

	E731 [29]	E773 [31]	PDG'92 [5]
$\varphi_{+-}[^o]$	42.2 ± 1.4	43.35 ± .70 ± .79	46.6 ± 1.2
$\Delta m[10^{10}\hbar s^{-1}]$	.5286 ± .0028	.5286 ± .0029 ± .0022	.5351 ± .0024
$\tau_S[10^{-10}s]$	.8929 ± .0016	.8929 ± .0014 ± .0014	.8922 ± .0020
$\varphi_{00} - \varphi_{+-}[^o]$	-1.6 ± 1.2	.67 ± .85 ± 1.1	-0.1 ± 2.0
$\varphi_{+-} - \varphi_{SW}[^o]$ (deduced)	-1.2 ± 1.4	0.0 ± 1.1	2.9 ± 1.2

Table 4: Results of E731 an E773 for the parameters relevant to the indirect CPT tests.

b) with Γ_S and Δm fixed to their measured values and letting this time the regeneration parameters, $\varphi_{00} - \varphi_{+-}, \varphi_{+-}$ and $\Re e(\epsilon'/\epsilon)$ free, the phase difference $\varphi_{00} - \varphi_{+-}$ remains compatible with zero, although its precision is improved with respect to the previous world average [5].

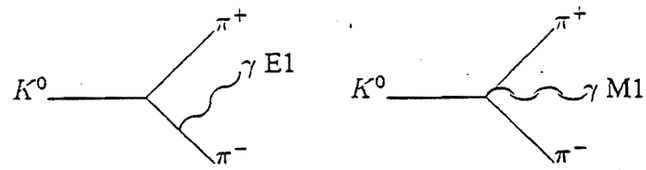
c) finally, with τ_S fixed to its measured value and letting free all other parameters, the value obtained for the phase φ_{+-} is well below the world average [5].
The new Δm value modifies the superweak phase slightly from $\varphi_{SW} = 43.7^0 \pm .2^0$ to $43.4^0 \pm .2^0$. The resulting phase difference $\varphi_{+-} - \varphi_{SW} = -1.2^0 \pm 1.4^0$ is statistically compatible with CPT conservation.

More recently [31], the E773 collaboration at Fermilab communicated preliminary results obtained from an on going experiment, dedicated to the study of the phase $\varphi_{2\pi}$ using the E731 apparatus. The "new" experiment uses different thickness regenerators for the two simultaneous neutral kaon beams used for the ϵ'/ϵ measurement. The results also presented in Table 4, confirm remarkably well the previous ones and specifically a Δm value which is by 2σ lower than the world average.
Final results from E773 and from CPLEAR should help clarifying this point in a complementary way. In regenerator experiments the $\Delta m/\varphi_{+-}$ correlation function must be precisely understood. On the other hand, experiments taking advantage of initially pure, tagged $K^0, \bar{K}^0$ beams, like CPLEAR measure Δm and φ_{+-} from two independent decay channels, i.e. the semileptonic and the 2π channel asymmetries respectively.

From table 4, the progress in the precision of the $\varphi_{+-} - \varphi_{SW}$ phase difference should reduce the present CPT test limit, based on the $\bar{K}^0 - K^0$ mass difference, of $\leq 4\ 10^{-18}$ [5] to $1.4 \leq 10^{-18}$. This does not include the contribution of $\approx 10^{-18}$ due the present uncertainties in the semileptonic and 3 π decay parameters, reflected in the phase of $\eta_{I=0}$.

3.5 The decays into the $\pi^+\pi^-\gamma$ final state

Neutral kaon decays to the $\pi^+\pi^-\gamma$ final state can proceed through internal Brehmstrahlung (IB) where one of the charged pions radiates a photon E1 or through direct photon emission (DE) where an M1 photon is emitted at the decay vertex, see Fig. 6. The first process is, like the two-pion decay channel, CP conserving for K_S and CP violating for K_L. The second one, as a three body final state is CP violating for K_S and CP-conserving for K_L. The study of $K_{L,S} \to \pi^+\pi^-\gamma$ decays and possibly the experimental evidence for CP violation in a direct emission (DE) process would be extremely interesting for the understanding of the CP-violation mechanism. Also, the $K_L \to \pi^+\pi^-\gamma$ (DE) spectrum represents an interesting observable for testing chiral perturbation models and the understanding of CP-violation is rare decays like $K_L \to \pi^0 e^+ e^-$. The DE process is dynamically suppressed with respect to the IB one, so that the observation of the CP violating K_S transition is rather difficult (see also [32]).
Since both the above processes may contribute to the $\pi^+\pi^-\gamma$ decay amplitudes, a CP-violation



CP violating K_L decay CP violating K_S decay

Figure 6: Internal Bremsstrahlung and Direct Emission decays of neutral Kaons into $\pi^+\pi^-\gamma$

parameter must be defined for a pure CP eigenstate. More specifically one can define

$$\eta_{+-\gamma} = \frac{A(K_L \to \pi^+\pi^-\gamma(E1))}{A(K_S \to \pi^+\pi^-\gamma(E1))} \tag{26}$$

for which, only if the DE process occurred through a E1 transition there would be mixing of the two forms of decays; in that case any difference $\eta_{+-\gamma} \neq \eta_{+-}$ would be a clear indication of direct CP-violation in $K_L \to \pi^+\pi^-\gamma$ decays.

The E731 collaboration [33, 34] collected 6859 $K_{L,S}$ decays (3136 K_L and 3723 K_S) into $\pi^+\pi^-\gamma$ and used their over 370000 $\pi^+\pi^-$ decays for normalization, to determine branching ratios of the K_L (DE and IB) and the $K_S \to \pi^+\pi^-\gamma$ transitions.

Fig. 7 shows the eigentime distribution of $\pi^+\pi^-\gamma$ decays compared to the Monte-Carlo simulation including an interference term (a) between K_L and K_S and without it (b). From this comparison evidence for the existence of $K_L - K_S$ interference was inferred, similar to the 2π decay mode. In view of fitting the data with the appropriate time development function in order to extract the

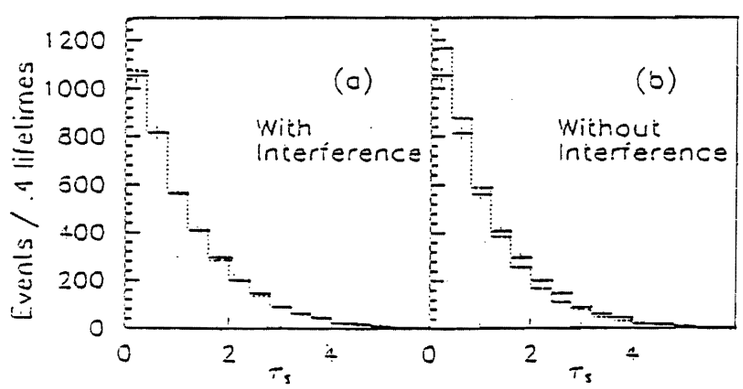


Figure 7: Proper time distribution of $\pi^+\pi^-\gamma$ decays from E731 [32] with (a) and without (b) a $K_S - K_L$ interference term.

CP violation parameter $\eta_{+-\gamma}$, these have been binned in kaon energy and in the longitudinal decay vertex distance. After background subtraction 53 statistically significant bins (3671 events) have been selected and corrected for acceptance, determined by Monte Carlo simulation to be 10% for K_L and 21% for K_S.

The K_L time development function used to fit the data included the DE process and $K_L - K_S$ interference; the CP violation parameters $\eta_{+-\gamma}$, $\varphi_{+-\gamma}$ and the overall normalization were left free, whereas the present world average values for $\tau_S, \tau_L, \Delta m$ were fixed. The result of the fit together with a rather conservative systematics estimate is [34]

$$|\eta_{+-\gamma}| = 2.15 \pm .26 \pm .20\ 10^{-3} \tag{27}$$

$$\varphi_{+-\gamma} = 72^o \pm 23^o \pm 7^o$$

It represents the first experimental evidence of $K_L - K_S$ interference in $\pi^+\pi^-\gamma$, corresponding to a CP violation parameter $\eta_{+-\gamma}$ (E1), in agreement within statistics, with the established CP violation parameter in the 2π channel.
The E773 collaboration has reported preliminary results also on this channel [31]: $\mid \eta_{+-\gamma} \mid = 2.414 \pm .065 \pm .062\, 10^{-3}$ and $\varphi_{+-\gamma} = 45.5^o \pm 3.6^o \pm 2.4^o$ which improve the precision on the amplitude by a factor ~ 4 and on the phase by ~ 6.

The upper limit on possible direct CP violation in this decay which can be deduced from the comparison with the present value [5] of the CP violation parameter in the 2π decay, η_{+-}, is $\mid \epsilon'_{+-\gamma} \mid / \epsilon < 0.1$.

4 Summary and conclusions

The results of the latest experiments devoted to the search of direct CP-violation could not provide unambiguous evidence for such a process, in the $K_L \to \pi\pi$ decay, at the level of $\Re e(\epsilon'/\epsilon) \leq 10^{-3}$. This result lies on the high side of present theoretical estimates. The next generation experiments, NA48 at CERN, E832 at Fermilab and KLOE at the ϕ factory, DAΦNE, aim at precisions of the order of (10^{-4}) in ϵ'/ϵ and are expected to enter their physics production phase late in 1996.
The first experiment using initially K^0 and $\bar{K}^0$ beams and measuring time dependent particle-antiparticle decay asymmetries, CPLEAR, produced already significant results, compared to the world's best values for φ_{+-}, Δm and x and first time measurements of ϵ_S, ϵ_T and δ_{CPT}. The experiment produces unique information to help disentangling CP from T and CPT violations and will run until the end of 1995.
DAΦNE appears as the next generation facility providing initially pure neutral kaons $(K_L K_S)$, therefore as a privileged place to pursue and enlarge the field of CP, T, CPT and quantum mechanics tests in the K^0 system, after CPLEAR.
The precision of the CP-violation parameter in the $\pi^+\pi^-\pi^0$ channel, η_{+-0}, has been improved by one order of magnitude and for the first time the CP-allowed K_S amplitude has been isolated.
First evidence for $K_S - K_L$ interference and CP violation in the internal Bremsstrahlung process $K_L \to \pi^+\pi^-\gamma$ has been established at Fermilab.
The precision of the indirect CPT test based on the $\varphi_{+-} - \varphi_{SW}$ difference is improved by a factor ≈ 2.5 with the new values of $\Im m(x)$ and $\eta_{3\pi}$.
The coherent analysis of all precisely measured parameters describing the $K^0 \to 2\pi$ decay channels lead to significant modifications of the phase φ_{+-} and of the phase difference $\varphi_{+-} - \varphi_{SW}$. This should improve the CPT test based on the $\bar{K}^0 - K^0$ mass difference by a factor of 3.
Although high precision CP, T and CPT studies in the K^0 system will dominate the near future of the CP violation field, the extension to the beauty sector is already engaged through the B-physics studies on electron and hadron colliders. Among them the CLEO collaboration at CESR/Cornell is expected to run with an upgraded detector and machine luminosities up to $\mathcal{L} \simeq 10^{33} cm^{-2} s^{-1}$, in 1997. The dedicated $B\bar{B}$ facility at SLAC and the BABAR detector should start operation end 1998 and represent the most promising place for discovering CP-violation in the B-meson sector, before the Large Hadron Collider at CERN.
Finally, the theoretical predictability in the field is expected to improve due to the new experimental constraints in both the kaon and the B-meson sectors as well as from progress in the evaluation of the non perturbative strong interaction vertices. Indeed, only through the quantitative comparison of the experimental results with theoretical (SM) predictions the nature of CP-violation and its relevance to possible "new physics", beyond the Standard Model, can be apprehended.

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