THE STUDY OF THE CP, T AND CPT SYMMETRIES IN THE CPLEAR EXPERIMENT

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Abstract

The CPLEAR experiment at CERN is presently measuring with high precision possible CP, T and CPT violation effects in the neutral kaon system through the observation of time dependent asymmetries between K^0 and $\overline{K^0}$. Results on the measurement of the CP, T and CPT violating parameters are reported in the $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$ and semileptonic decay channels. Present precisions are already at the level of the word average value (Φ_{+-}) or even one order of magnitude better (η_{+-0}).

1 Introduction

So far, CP violation has only been observed by using pure K_L beams, in decays of neutral kaons into two pions final states ($\pi^+\pi^-$,$\pi^0\pi^0$[1] and recently $\pi^+\pi^-\gamma$[2]) and in the charge asymmetry of semileptonic K_L decays. Rather than studying the physical states K_S and K_L, the CPLEAR experiment is unique in making direct use of the flavour eigenstates K^0 and $\overline{K^0}$ [3]. The method of CPLEAR experiment takes advantage of the fact that the K^0 and $\overline{K^0}$ are symmetrically produced at low momenta ($\leq$ 800 MeV/c) which gives a typical decay length of ~ 2.5 cm for the K_S. Therefore, the interference pattern is fully contained inside the detector. For the decay into two pions, the decay rates of initial K^0 and $\overline{K^0}$ are given by :

$$\left.\begin{array}{l} R(K^0 \to \pi^+\pi^-)(t) \\ R(\overline{K^0} \to \pi^+\pi^-)(t) \end{array}\right\} \propto e^{-\gamma_S t} + |\eta_{+-}|^2 e^{-\gamma_L t} \pm 2\,|\eta_{+-}|\, e^{\frac{-(\gamma_S+\gamma_L)t}{2}} \cos(\Delta m t - \Phi_{+-}),$$

where γ_S et γ_L are the decay widths of K_S and K_L. The parameter η_{+-} is defined as the ratio of the CP forbidden to CP allowed amplitudes :

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

The corresponding decay rate asymmetry defined as :

$$A_{+-}(t) = \frac{R(\overline{K^0} \to \pi^+\pi^-)(t) - R(K^0 \to \pi^+\pi^-)(t)}{R(\overline{K^0} \to \pi^+\pi^-)(t) + R(K^0 \to \pi^+\pi^-)(t)} \tag{1}$$

is sensitive to the interference term and therefore to the magnitude and the phase of the ratio η_{+-}. $A_{+-}(t)$ is related to the parameters $|\eta_{+-}|$ and Φ_{+-} through the equation :

$$A_{+-}(t) \approx 2Re(\varepsilon_L) - \frac{2\,|\eta_{+-}|\, e^{\frac{(\gamma_S-\gamma_L)t}{2}} \cos(\Delta m t - \Phi_{+-})}{1 + |\eta_{+-}|^2\, e^{(\gamma_S-\gamma_L)t}} \tag{2}$$

where ε_L is the CP-violating mixing parameter related to the K_L.

Similar asymmetries may be reconstructed and observed in other channels such as $\pi^+\pi^-\pi^0$ and $\pi e\nu$ final states. By using these asymmetries, it is also possible to study the T and CPT violating parameters. Actually, the CPLEAR experiment allows several tests of the discrete symmetries (T,CP,CPT) to be done simultaneously in the same detector :

CP violation : Measurement of η_{+-} and η_{+-0}.

T violation : In the semileptonic channel ($\pi e\nu$), measurement of the T violating parameter $\varepsilon_T = (\varepsilon_S + \varepsilon_L)/2$[1].

CPT violation : By comparing the phase Φ_{+-} with $\Phi_{SW} = \arctan(2\Delta m/(\gamma_S - \gamma_L))$, it is possible to test the CPT invariance. Indeed, according to the Bell-Steinberger unitarity relation the value of Φ_{+-} is expected to be close to Φ_{SW}[4].
In addition the semileptonic channel gives access to the measurement of the CPT violating parameter $\delta_{CPT} = (\varepsilon_S - \varepsilon_L)/2$

[1] ε_S and ε_L are the CP violating mixing parameters related to K_S and K_L, ie $K_S = 1/\sqrt{2}(K_1^0 + \varepsilon_S K_2^0)$ and $K_L = 1/\sqrt{2}(K_2^0 + \varepsilon_L K_1^0)$.

2 The CPLEAR experiment

At LEAR, the K^0 and $\overline{K^0}$ mesons are symmetrically produced in proton-antiproton annihilations at rest through the reactions

$$\begin{aligned} p\bar{p} &\rightarrow K^-\pi^+K^0, \qquad Br = 2\times10^{-3} \\ p\bar{p} &\rightarrow K^+\pi^-\overline{K^0}, \qquad Br = 2\times10^{-3}\,. \end{aligned} \tag{3}$$

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

The detector is shown in figure 1, displaying a typical event of the type $p\bar{p} \rightarrow K^+\pi^-\overline{K^0}$ and the subsequent decay of the $\overline{K^0}$ into $\pi^+\pi^-$. The detector 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. These antiprotons are stopped 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 on-line 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 $K^\pm$ 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) for a high spatial resolution on photon and electron showers.

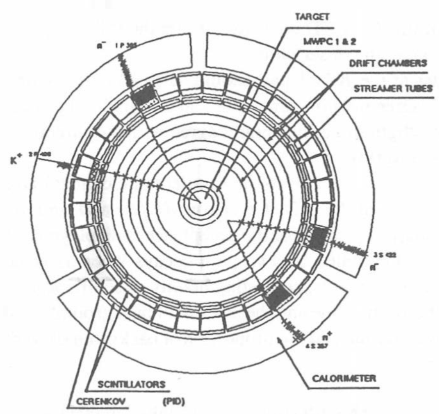

Figure 1: *Transversal view of the CPLEAR detector with a* $\overline{K^0} \rightarrow \pi^+\pi^-$ *decay.*

Because of the small branching ratio of the desired channels (3), the experiment requires a high annihilation rate of about 1 MHz. In order to provide an efficient online event selection and to reject the background, a sophisticated multi-level trigger has been designed. It is based on the recognition of the associated $K^{\pm}\pi^{\mp}$ pair at the annihilation vertex. The process is initiated by a beam counter signal when the antiproton enters the target. The first requirement is that there are at least two hits in the inner scintillator with at least one charged kaon candidate ($S\overline{C}S$ from the PID). The next stages impose kinematical constraints on the event firstly by applying a cut on the transverse momentum of the kaon candidate, and then requiring 2 or 4 charged tracks after fast on-line tracking and a full track parametrization. The following stage constrains the particle identification by using the energy loss of the kaons and the pions in the scintillators, the time of flight difference between kaons and pions and the number of photo-electrons in the Čerenkov-counter. The last stage requires a minimum number of clusters in the calorimeter for 2 charged track events. The maximum trigger decision time is around 34 μs and its reduction factor is about 1000. At a beam intensity of 1 MHz, the data acquisition system writes about 450 events per second on tape.

The experiment has achieved data taking with the fully instrumented detector and trigger in 1992. The results and the expected statistical errors are based on the 1992 data, which represents about 15 millions of neutral kaon decays to $\pi^+\pi^-$, 36000 decays to $\pi^+\pi^-\pi^0$ and 150000 decays to $\pi e\nu$. In the case of the $\pi^+\pi^-$ and semileptonic analysis, earlier data sets (1990 and 1991)[2] are merged.

3 $\pi^+\pi^-$ final states

In the offline analysis[6], 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 constraints fits to minimize the residual background from three pions and semileptonic final states and to improve the resolution on the measured K^0 decay length (0.1 τ_S after constrained fits). The constraints are the following :

- energy and momentum conservation,
- the missing mass of the $K^{\pm}\pi^{\mp}$ pair should be equal to the neutral kaon mass,
- for each vertex, agreement of transverse and longitudinal projection,
- the neutral kaon flight direction should agree with the direction between the annihilation vertex and the decay vertex.

The background comes mainly from the semileptonic channel and half of it is removed by identifying the electron in the PID (Čerenkov, dE/dx and time of flight). The K^0 and $\overline{K^0}$ decay time distribution corrected for the acceptance is displayed in figure 2. For proper times $t \lesssim 10\tau_S$ it is clearly dominated by two-pion decays whereas at large lifetime a significant fraction of background remains, consisting mainly of semileptonic K_L decays. From a fit to the data, leaving the K_S lifetime and the amount of background K_L decays as free parameters, the value for the K_S lifetime and the proportion of background over the long-lived component were found to be :

$$\begin{aligned} \tau\ (\mathrm{K}_S\ \text{lifetime}) &= (1.006 \pm 0.004) \times \tau_S \\ \text{Background} &= 1.21 \times R(\mathrm{K}_L \to \pi^+\pi^-) \end{aligned}$$

[2] These data have been recorded with a temporary trigger which selected events with a lifetime $\geq 4\tau_S$.

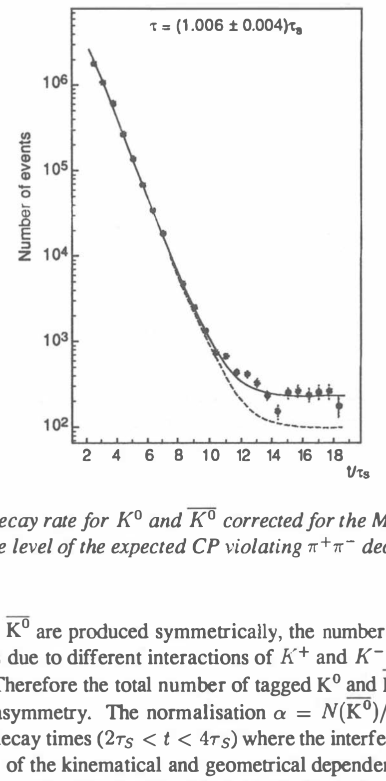

Figure 2: *The $\pi^+\pi^-$ decay rate for K^0 and $\overline{K^0}$ corrected for the Monte-Carlo acceptance. The dashed curve is the level of the expected CP violating $\pi^+\pi^-$ decay.*

Even if the K^0 and $\overline{K^0}$ are produced symmetrically, the number of tagged K^0 and $\overline{K^0}$ is not exactly equal. It is due to different interactions of K^+ and K^- in the detector material (essentially the PID). Therefore the total number of tagged K^0 and $\overline{K^0}$ has to be normalized before extracting the asymmetry. The normalisation $\alpha = N(\overline{K^0})/N(K^0)$ was determined from the data at short decay times ($2\tau_S < t < 4\tau_S$) where the interference is small compared to α. After corrections of the kinematical and geometrical dependences, the statistical error on the normalisation factor α is about 0.002. The figure 3 shows the asymmetry A_{+-} defined in equation 1. The parameters $|\eta_{+-}|$ and Φ_{+-} are extracted from the fit (solid line) of the asymmetry A_{+-} between $4\tau_S$ and $10\tau_S$. In this fit the normalisation factor and the proportion of background are fixed.

$$
\begin{aligned}
|\eta_{+-}| &= (2.25 \pm 0.07_{stat} \pm 0.02_{sys}) \times 10^{-3} \\
\Phi_{+-} &= 44.70^\circ \pm 1.30^\circ_{stat} \pm 0.75^\circ_{sys} \pm 0.70^\circ_{\Delta m}
\end{aligned}
$$

The main source of systematic errors on Φ_{+-} comes from the determination of the normalisation factor ($\pm 0.7^\circ$) which will decrease with higher statistics which is already available now. The second source of systematic errors ($\pm 0.3^\circ$) on Φ_{+-} and $0.02.10^{-3}$ on $|\eta_{+-}|$ is due to uncertainties on the correction for the regeneration effects in the energy range of this experiment. Finally, we have to take the limited knowledge of Δm into account. It induces an uncertainty of $\pm 0.7^\circ$ on Φ_{+-}. But it is also possible to measure Δm in the semileptonic channel and to improve the accuracy on Δm.

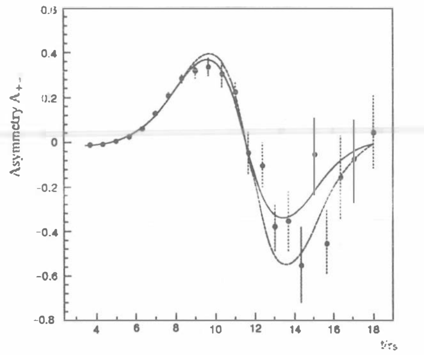

Figure 3: *The solid curve shows the fit of the asymmetry A_{+-} with background estimated in the decay. The dashed line is assuming no background.*

4 $\pi e \nu$ final states

Several parameters can be measured from the observation of $\pi e \nu$ decays. First, as already mentioned, a precision measurement of Δm can be done by using the asymmetry $A_{\Delta \mathrm{m}}$(6). Then, the CPT and T symmetries can be tested by measuring the two parameters δ_{CPT} and ε_T which depend on ε_S and ε_L, the CP violating mixing parameters related to K_S and to K_L ($\varepsilon_S = \varepsilon_T + \delta_{CPT}$ and $\varepsilon_L = \varepsilon_T - \delta_{CPT}$). Indeed, if CPT symmetry holds in the mixing matrix, ε_S is expected to be equal to ε_L (ie $\delta_{CPT} = 0$).

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 $\overline{K^0}$ can only decay to $\pi^+ e^- \bar{\nu}_e$. Therefore the charge of the lepton $e^\pm$ is a marker of the stageness at the decay level, whereas the charge of the kaon $K^\pm$ is a marker of the type of the neutral kaon at the production level. We can define two different kinds of rates : The two first rates(4) correspond to events with particle/antiparticle oscillations whereas the rates(5) correspond to events without oscillation.

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

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

By comparing the rates without oscillation(5) with the rates with oscillations(4), the oscillation frequency Δm can be determined from the asymmetry $A_{\Delta \mathrm{m}}(t)$ independently of the CP violation parameters :

$$A_{\Delta \mathrm{m}}(t) = \frac{N^+ + \overline{N}^- - (\overline{N}^+ + N^-)}{N^+ + \overline{N}^- + \overline{N}^+ + N^-} = \frac{2\cos(\Delta \mathrm{m}\, t)\ e^{-\frac{1}{2}(\gamma_S + \gamma_L)t}}{e^{-\gamma_S t} + e^{-\gamma_L t}}\ . \tag{6}$$

Assuming the $\Delta S = \Delta Q$ rule, a non-zero value of the asymmetry $A_T(t)$ defined as

$$A_T(t) = \frac{\overline{N}^+ - N^-}{\overline{N}^+ + N^-} \tag{7}$$

would reflect a difference in the oscillation probabilities $P(K^0 \to \overline{K^0})$ and $P(\overline{K^0} \to K^0)$ and would be a proof of T violation which is expressed by the parameter ε_T. The A_T asymmetry gives access to the measurement of ε_T : $A_T(t) = 4Re(\varepsilon_T)$. Similarly, the CPT violating parameter δ_{CPT} may be measured in the asymmetry $A_{CPT}(t)$ defined as

$$A_{CPT}(t) = \frac{\overline{N}^- - N^+}{\overline{N}^- + N^+} \simeq 4Re(\delta_{CPT}) \ . \tag{8}$$

The semileptonic events are selected using kinematical constrained fits and by identifying the electron (or positron) from the neutral kaon decay. The e/π separation is achieved, for momenta below 350 MeV/c, by using PID (dE/dx, time of flight and Čerenkov signal). Fits of the asymmetry $A_{\Delta\mathrm{m}}(t)$ (figure 4) and of the two other asymmetries(7,8) give the following results :

$$\begin{aligned} \Delta\mathrm{m} &= (0.524 \pm 0.006_{stat} + 0.002_{sys}) \times 10^{10}\hbar s^{-1} \\ A_T(t) &= (0 \pm 4_{stat} \pm 8_{sys}) \times 10^{-3} \\ Re(\delta_{CPT}) &= (0 \pm 1_{stat} \pm 2_{sys}) \times 10^{-3} \end{aligned}$$

The systematic errors are due mainly to uncertainties in normalisation of the charged kaons and the charged leptons, which will decrease considerably with higher statistics.

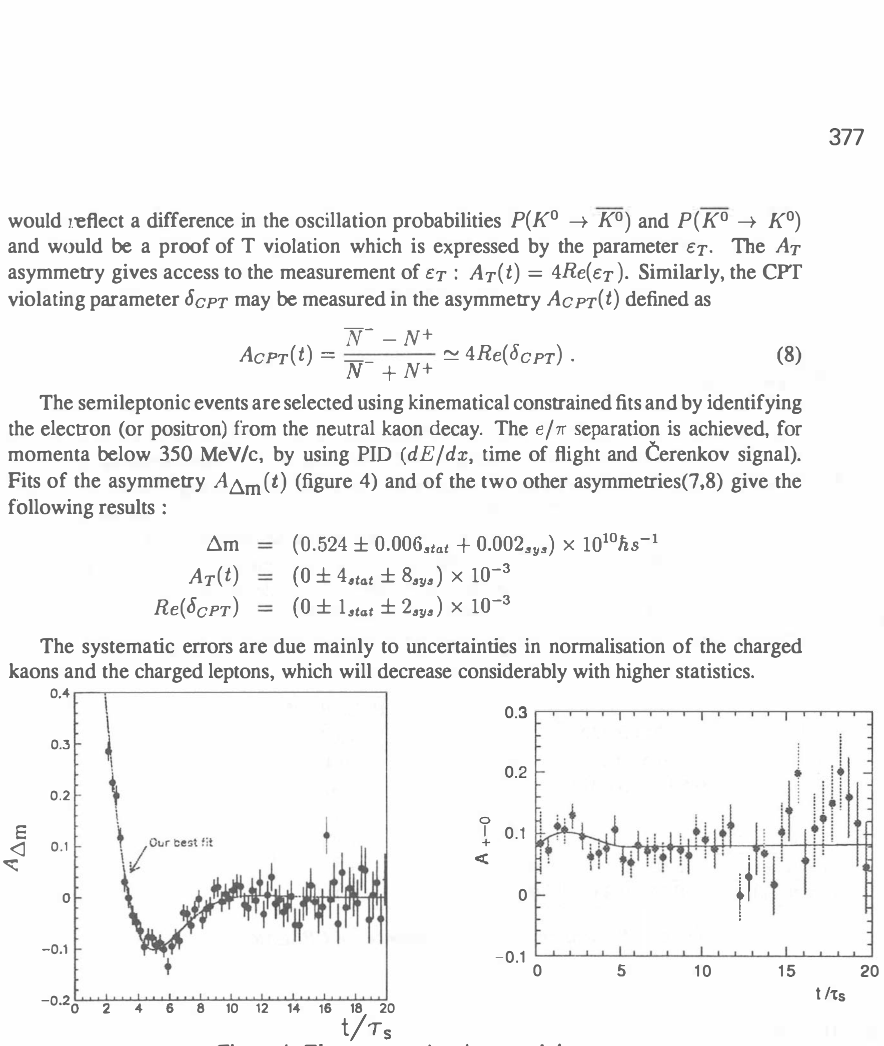

Figure 4: *The asymmetries $A_{\Delta m}$ and A_{+-0}*

5 $\pi^+\pi^-\pi^0$ final states

The $\pi^+\pi^-\pi^0$ state can have a CP eigenvalue of +1 or -1, depending on the angular momentum of the three pions. But the CP conserving part of the K_S-K_L interference term is antisymmetric with respect to the $\pi^+\pi^-$ momentum difference in the kaon rest frame and it vanishes when it is integrated over the whole Dalitz plot. Therefore, a non-zero value of the asymmetry A_{+-0} is a proof of CP violation.

$$A_{+-0}(t) = \frac{R(\overline{\mathrm{K}^0}_{t=0})(t) - R(\mathrm{K}^0_{t=0})(t)}{R(\overline{\mathrm{K}^0}_{t=0})(t) + R(\mathrm{K}^0_{t=0})(t)} \approx 2Re(\epsilon_S) - 2\,|\eta_{+-0}|\, e^{\frac{-(\gamma_S-\gamma_L)t}{2}} \cos(\Delta\mathrm{m}\, t + \Phi_{+-0})$$

A fit of the time dependent asymmetry shown on figure 4 gives the following value of the CP violating parameter η_{+-0} :

$$\begin{cases} \mathrm{Re}(\eta_{+-0}) &= 0.002 \pm 0.016_{stat} \\ \mathrm{Im}(\eta_{+-0}) &= 0.044 \pm 0.026_{stat} \end{cases}$$

6 Conclusions

These preliminary results have demonstrated the validity of the CPLEAR approach based on the comparison of the decay properties of particles and antiparticles. The measurements of the CP violating parameters η_{+-} and Φ_{+-} are in agreement with the world average values [1] and the value of $\Phi_{SW} = 43.7° \pm 0.2°$. For the first time, in the semileptonic decay, the CPT and T symmetries are tested and this analysis will soon give a precise measurement of Δm which can be use in the determination of Φ_{+-}. The accuracy of the measurement of the real part and the imaginary part of η_{+-0} has already improved by one order of magnitude with the 1992 data of CPLEAR. The table 6 summarizes the goal of CPLEAR in statistical precision compared to what has been already achieved[1] and to the current best measurements[7].

	PDG '92	CPLEAR '92	CPLEAR '95
$\lvert\eta_{+-}\rvert$ $[10^{-3}]$	2.279±0.022	2.25±0.07	±0.02
Φ_{+-} [°]	46.5±1.2	44.7±1.3	±0.4
Δm $[10^{10}\hbar/s]$	0.5351±0.0024	0.524±0.006	±0.002
A_T $[10^{-3}]$	-	0±4	±1
$\Re e(\delta_{CPT})$ $[10^{-3}]$	-	0±1	±0.25
$\Re e(\eta_{+-0})$	0.05±0.17	0.002±0.016	±0.004
$\Im m(\eta_{+-0})$	0.15±0.33	0.044±0.026	±0.006

Table 1: *Present and futur performances of CPLEAR*

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