CP, T, AND CPT VIOLATION IN THE NEUTRAL KAON SYSTEM AT THE CPLEAR EXPERIMENT

The CPLEAR Collaboration

R. Adler[2], T. Alhalel[2], A. Angelopoulos[1], A. Apostolakis[1], E. Aslanides[11], G. Backenstoss[2], C.P. Bee[11], O. Behnke[17], J. Bennet[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], M. Danielsson[15], A. Cody[9], S. Dedoussis[16], M. Dejardin[4], J. Derre[14], M. Dodgson[9], J. Duclos[14], A. Ealet[11], B. Eckart[2], C. Eleftheriadis[16], I. Evangelou[8], L. Faravel [7,11], 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. Garnet[9], D. Garreta[14], T. Geralis[13], H.-J. Gerber[17], A. Go[3], P. Gumplinger[17], C. Guyot[14], A. Haselden[9], P.J. Hayman[9], F. Henry-Couannier[11], R.W. Hollander[6], E. Hubert[11], K. Jansson[15], H.U. Johner[7], K. Jon-And[15], P.R. Kettle[13], C. Kochowski[14], P. Kokkas[8], R. Kreuger[6], T. Lawry[3], R. Le Gac[11], F. Leimgruber[2], A. Liolios[16], E. Machado[5], P. Maley[9], 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], P. Pavlopoulos[2], F. Pelucchi[11], J. Pinto da Cunha[5], A. Policarpo[5], G. Polivka[2], H. Postma[6], R. Rickenbach[2], B.L. Roberts[3], E. Rozaki[1], T. Ruf[4], L. Sacks[9], 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[4], C. Touramanis[9], F. Triantis[8], D.A. Tröster[2], E. Van Beveren[5], C.W.E. Van Eijk[6], S. Vlachos[2], P. Weber[17], O. Wigger[13], C. Witzig[17], M. Wolter[17], C. Yeche[14], D. Zavrtanik[10] and D. Zimmerman[3].

[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, [13]Paul-Scherrer-Institut (PSI), [14]DAPNIA/SPP CE Saclay, [15]KTH Stockholm, [16]University of Thessaloniki, [17]ETH-ITP Zürich.

Presented by D. Garreta
DAPNIA/SPP, CE Saclay, Gif-sur-Yvette, France

Abstract

The essential characteristics of the neutral kaon system and the way CP, T, and possible CPT violations may be observed in it are recalled. The principle of the CPLEAR experiment is presented. CPLEAR experimental results in the semi-leptonic decay channels are given and discussed. It is shown, in particular, that direct time reversal invariance violation will be experimentally observed for the first time.

1 INTRODUCTION

CP violation was first observed in the long-lived neutral kaon decaying[1] into $\pi^+\pi^-$. We will first recall the essential characteristics of the neutral kaon system. Then we will show how CP, T, and CPT symmetries come in and how their eventual violation can be observed. The principle of the CPLEAR experiment will be explained[2]. Finally CPLEAR experimental results in the semi-leptonic decay channels will be given and discussed. We will show, in particular, that in the CPLEAR experiment, for the first time, direct T violation will be experimentally observed.

2 NEUTRAL KAON SYSTEM

We first describe the neutral kaon system assuming that CP symmetry is valid.

Neutral kaons are produced under the form $|K^0\rangle = |\bar{s}d\rangle$, $S = +1$, $|\overline{K}^0\rangle = |s\bar{d}\rangle$, $S = -1$ with a well defined strangeness S.

Once strong interaction cannot do anything more to the neutral kaon, weak interaction has time to induce, among other things, $\Delta S = 2$ transitions that produce $K^0 \Longleftrightarrow \overline{K}^0$ oscillations (see Fig. 1).

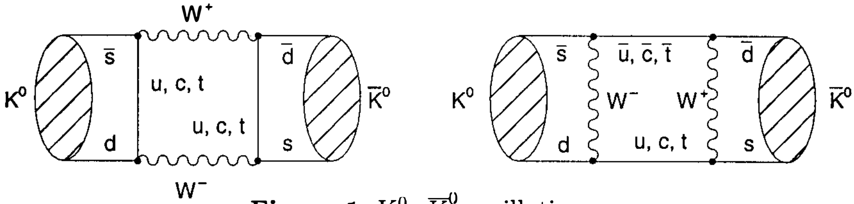

Figure 1: K^0, $\overline{K}^0$ oscillations

The two neutral kaon physical states are K_S and K_L with very different lifetimes, due to phase-space conditions. By looking at their decay channels (see Table 1), they can be shown to be the symmetric and antisymmetric combinations of K^0 and $\overline{K}^0$, that is the CP eigenstates K_1 and K_2 with eigenvalues $+1$ and -1, $|K_1\rangle = (|K^0\rangle + |\overline{K}^0\rangle)/\sqrt{2}$, $|K_2\rangle = (|K^0\rangle - |\overline{K}^0\rangle)/\sqrt{2}$.

Table 1 Neutral kaon main decay channels

$\vert K_S\rangle$	$\rightarrow \vert\pi^+\pi^-\rangle$ 69%	CP = +1	$M_S \simeq 498$ MeV
	$\rightarrow \vert\pi^0\pi^0\rangle$ 31%		$\tau_S = 1/\Gamma_S \simeq 0.09$ns
$\vert K_L\rangle$	$\rightarrow \vert\pi^+\pi^-\pi^0\rangle$ 12.4%	CP = −1	$M_L \simeq 498$ MeV
	$\rightarrow \vert\pi^0\pi^0\pi^0\rangle$ 21.6%	$(\ell = 0)$	$\tau_L = 1/\Gamma_L \simeq 52$ns
	$\rightarrow \vert\pi^+\mu^-\bar{\nu}_\mu\rangle$, $\vert\pi^-\mu^+\nu_\mu\rangle$ 27%		
	$\rightarrow \vert\pi^+e^-\bar{\nu}_e\rangle$, $\vert\pi^-e^+\nu_e\rangle$ 39%		

Once a K^0 is produced, its K_S and K_L components evolve according to their masses and widths. The probabilities of finding a K^0 or a $\overline{K}^0$ at a time t after production can easily be calculated.

$$\begin{matrix}\mathcal{P}(K^0,t) \\ \mathcal{P}(\overline{K}^0,t)\end{matrix} = \frac{1}{4}\{\exp[-\Gamma_S t] + \exp[-\Gamma_L t] \pm 2\exp[-(\Gamma_S + \Gamma_L)t/2]\ \cos[\Delta m t]\}$$

An interference term clearly shows up between the K_S and K_L decay terms. The essential characteristics of the neutral kaon system is that the $\Delta m = M_L - M_S$ term that drives this interference is about the same as the decay constant $\Gamma_S/2$. This means that this interference pattern has time to show up before it is killed by the decay. We will see that this effect is experimentally observable in the semi-leptonic decay charge asymmetry of a K^0 (or a $\overline{K}^0$) beam because of the $\Delta S = \Delta Q$ rule that relates directly the charge of the lepton to the strangeness of the kaon (see Fig. 2).

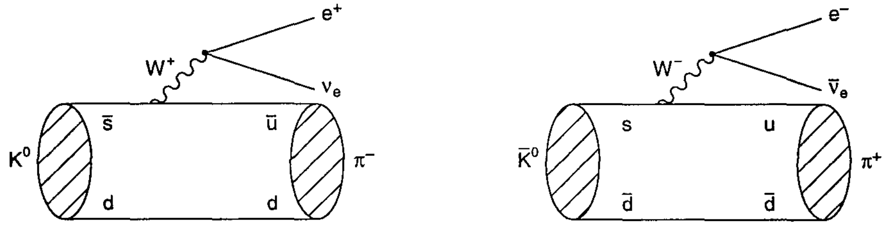

Figure 2: K^0, $\overline{K}^0$ semileptonic decay

3 CP, T, AND CPT VIOLATION

The fact that 2×10^{-3} K_L also decayed into $\pi^+\pi^-$[1] showed that CP was violated somewhere. This can happen in two places:

$$\begin{array}{ccccc} & \text{CP} & +1 = +1 & & +1 \neq -1 \\ \langle 2\pi|H|K_L\rangle & = & \varepsilon_L\langle 2\pi|H|K_1\rangle & + & \langle 2\pi|H|K_2\rangle \\ & & \text{(I)} & & \text{(II)} \end{array}$$

(I) In the production: K_S and K_L may no longer be the CP eigenstates K_1 and K_2 but there could be a small admixture of the other component. $|K_S\rangle = |K_1\rangle + \varepsilon_S|K_2\rangle$; $|K_L\rangle = \varepsilon_L|K_1\rangle + |K_2\rangle$; $|\varepsilon_S|$, $|\varepsilon_L| \ll 1$; $\varepsilon_S = \varepsilon + \delta$; $\varepsilon_L = \varepsilon - \delta$; ε and δ, sometimes referred to as ε_T and δ_{CPT}, can be shown[3] to correspond to T and CPT violations respectively.

(II) In the decay: The main component K_2 of K_L can also decay directly into 2π through a CP violating transition (penguin diagram). This direct CP violating term is parametrized through a coefficient ε', which is measured[4,5] to be at most a few 10^{-3} of ε.

3.1 CP-violating amplitude measurements

The CP-violating amplitude to a final CP eigenstate F is parametrized by a complex number η_F which is its ratio to the CP conserving amplitude. The decay rate of a $K^0(\overline{K}^0)$ beam into F $= 2\pi$ shows again an interference term between the allowed K_S decay and the CP forbidden K_L decay:

$R(K^0, F; t)$

$$= C_{\mp}(e^{-\Gamma_S t} + |\eta_F|^2 e^{-\Gamma_L t} \pm 2|\eta_F| e^{-(\Gamma_S+\Gamma_L)t/2} \cos(\Delta m t - \phi_F))$$

$R(\overline{K}^0, F; t)$

where $C_{\mp} = \frac{1 \mp 2\,\mathrm{Re}\,(\varepsilon)}{2} |\langle F|H|K_S\rangle|^2$.

A first method to get information about η_F is to compare the K_S and K_L decay rates. It gives $|\eta_F|^2$ and has been used by NA31[4] at CERN and E731[5] at Fermilab to measure ε'/ε.

A second method used by CPLEAR consists of measuring the decay rate asymmetry of K^0 and $\overline{K}^0$ in the interference region, which provides not only $|\eta_F|$ but also ϕ_F. It can be calculated that this asymmetry can go up to 60% at t$\sim$ 13.5 τ_S, which means that at this lifetime the rate of K^0 decay to $\pi^+\pi^-$ is four times larger than that of $\overline{K}^0$. Starting from $|\eta_F| \sim 2 \times 10^{-3}$ the observable effect, the ratio of rates between initial particles and antiparticles, goes up to four, typical of interferometry where a small signal is strongly enhanced by interfering with a large one. In addition CPLEAR uses the K_S decay region to calibrate the respective K^0 and $\overline{K}^0$ detection efficiencies.

Coming back to the semi-leptonic decay charge asymmetry, in addition to the interference pattern due to $K^0 \Longleftrightarrow \overline{K}^0$ oscillations, CP violation adds, for large decay times, a residual asymmetry 2 Re (ε) which has the same sign for K^0 and $\overline{K}^0$.

This leads to an absolute definition of what we call matter and antimatter. In a world made of matter this residual asymmetry has the sign of the nuclei of the chemical elements; in a world made of antimatter it would be the opposite.

4 CPLEAR EXPERIMENT

The CPLEAR experiment uses the annihilation at rest of the low-energy antiproton beam of LEAR at CERN on a hydrogen target. It selects the annihilation channels leading to a neutral kaon and a pair of charged K and π mesons. By detecting and measuring the momenta of the charged mesons tagged neutral kaons with known momentum and initial strangeness are produced.

Two essential features of the CPLEAR experiment are the following: K^0 and $\overline{K}^0$ are produced with the same rates and they have low momenta ($\leq$ 800 MeV/c), which gives a typical decay length of $\sim$ 2.5 cm for the K_S so that the interference pattern is fully contained inside the detector. The simultaneous detection of the K^0 and the $\overline{K}^0$ together with their decay products to many channels allows for, by using rate asymmetries between $\overline{K}^0$ and K^0, the cancellation of many systematic errors.
The decay channels studied are: 2π; 3π; semi-leptonic $\pi^+\ell^-\bar{\nu}_\ell$ and $\pi^-\ell^+\nu_\ell$.

5 CPLEAR EXPERIMENTAL RESULTS IN THE SEMI-LEPTONIC DECAY CHANNELS

Four decay rates are measured:

$$R^+ = R\,(K^0 \Rightarrow \pi^-\ell^+\nu_\ell, t), \qquad \overline{R}^- = R\,(\overline{K}^0 \Rightarrow \pi^+\ell^-\bar{\nu}_\ell, t)$$
$$R^- = R\,(K^0 \Rightarrow \pi^+\ell^-\bar{\nu}_\ell, t), \qquad \overline{R}^+ = R\,(\overline{K}^0 \Rightarrow \pi^-\ell^+\nu_\ell, t)$$

The last two are directly forbidden by the $\Delta S = \Delta Q$ rule implying, to be non zero, that at least one $K^0 \Longleftrightarrow \overline{K}^0$ transition has occured.

A possible violation of this rule is characterized by the parameter:

$$x = \langle \pi^-\ell^+\nu_\ell|H|\overline{K}^0\rangle / \langle \pi^-\ell^+\nu_\ell|H|K^0\rangle.$$

From the four rates the following four asymmetries can be built:

$$A_1(t) = \frac{(R^+ - R^-) - (\overline{R}^+ - \overline{R}^-)}{(R^+ + R^-) + (\overline{R}^+ + \overline{R}^-)} \text{ and } A_T(t) = \frac{\overline{R}^+ - R^-}{\overline{R}^+ + R^-} = 4\,\mathrm{Re}\,(\varepsilon_T) \text{ for } x = 0,$$

are shown in Fig. 3.

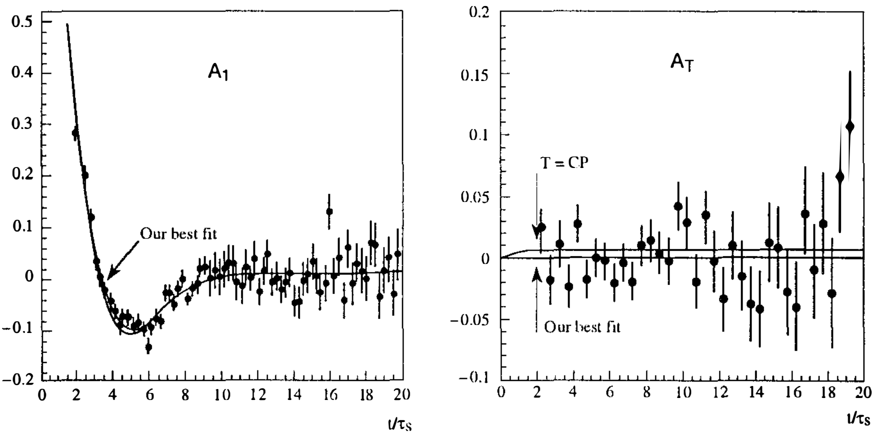

Figure 3: A_1, A_T semi-leptonic asymmetries

• A_1 (t) is sensitive to Δm and Re (x). Since it is roughly the charge asymmetry of a K^0 beam minus that of a $\overline{K}^0$ beam, the interference pattern adds up and is clearly visible and the residual asymmetry 2Re(ε) cancels out.
• A_T (t) is expected to be $\sim 6 \times 10^{-3}$. If the $\Delta S = \Delta Q$ rule holds it can only be different from zero through a first $K^0 \Longleftrightarrow \overline{K}^0$ step. Therefore it is a direct measurement of T violation.
• $A_2(t) = \dfrac{(\overline{R}^+ + \overline{R}^-) - (R^+ + R^-)}{(\overline{R}^+ + \overline{R}^-) + (R^+ + R^-)}$ is sensitive to Re (ε_S) and Im (x).
• $A_{CPT}(t) = \dfrac{\overline{R}^- - R^+}{\overline{R}^- + R^+} \rightarrow 4$ Re (δ) for $t \gg \tau_S$ is related to CPT violation.

6 CONCLUSION

Table 2 shows the statistical precision (1σ) of the parameters measured at CPLEAR together with the precision on these parameters quoted by the Particle Data Group (PDG)[6] before CPLEAR.

Table 2 Present and future performances of CPLEAR.

Parameter	PDG ('92)	'92	'93	'94 & '95
Δm $[10^{10}\hbar/s]$	0.0024	0.006	0.003	0.002
Re (x) $[10^{-3}]$	18	20	10	5
Im (x) $[10^{-3}]$	26	8	4	2
Re $(\varepsilon_S)[10^{-3}]$	–	1.4	0.7	0.4
$A_T[10^{-3}]$	–	4	2	1

It can be seen that at the completion of the experiment in 1995, taking into account systematic errors, the accuracy on Re (x) and Im (x) should be improved by factors of 3 and 10 respectively. Another striking feature is that a non-zero value of time reversal invariance violation should be directly measured at a four-standard deviation level.

References

[1] J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys. Rev. Lett. **13** (1964) 138.
[2] E.Gabathuler and P. Pavlopoulos, Proc. of the Workshop on Physics at LEAR with Low-Energy Cooled Antiprotons, ed. U.Gastaldi and R.Klapisch (Plenum, New York, 1982), p. 747.
[3] J.S. Bell and J. Steinberger, Proc. Conf. on Elementary Particles, Oxford 1965 (Rutherford Lab., Chilton, Didcot, 1966), p. 195.
[4] G.D.Barr et al., Phys. Lett. **B317** (1993) 233.
[5] L.K.Gibbons et al., Phys. Rev. Lett. **70** (1993) 1203.
[6] Particle Data Group, Phys. Rev. **D45** (1992).