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TIME REVERSAL, CP AND CPT VIOLATION STUDIES IN THE CPLEAR EXPERIMENT AT CERN

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Abstract: The CPLEAR experiment at CERN studies Time Reversal, CP and CPT symmetries in the neutral kaon system, which is so far the only system where CP violation has been observed. In the so-called ‘golden channels’, proton-antiproton annihilation produces a neutral kaon, a charged kaon and a charged pion. The strangeness of the neutral kaon is tagged with the charge of the accompanying kaon. Decay rate asymmetries between K^0 and $\overline{\mathrm{K}}^0$ are measured. Symmetry violating parameters connected to Time Reversal, CP and CPT symmetries are extracted from decays to various final states.

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1. Introduction

Neutral kaons are the lightest strange mesons and the only system where violation of matter-antimatter symmetry has been seen. This violation is connected to a CP-violating term in the K^0 - $\overline{\mathrm{K}}^0$ mixing matrix. On the other hand, strong theoretical arguments support CPT invariance. Given CPT invariance and CP violation, Time Reversal has to be violated.

The CPLEAR experiment [1] used a new experimental method to study T, CP and CPT symmetries in the decay of neutral kaons by measuring the rate asymmetries between K^0 and $\overline{\mathrm{K}}^0$ decays to various final states, namely $\pi^+\pi^-$, $\pi e\nu$, $\pi^+\pi^-\pi^0$, $\pi^0\pi^0$ and $\pi^0\pi^0\pi^0$. The extraction of the physics parameters is obtained through the measurements of the time-dependent decay rate asymmetries :

$$A_f(t) \;=\; \frac{R_{\overline{K}^0\to\overline{f}}(t) - R_{K^0\to f}(t)}{R_{\overline{K}^0\to\overline{f}}(t) + R_{K^0\to f}(t)}\ .$$

For instance the CP-violation parameter η_{+-} is obtained from the decay rates to $\pi^+\pi^-$ and the CPT-violation parameter $Re(\delta)$ is measured from the semileptonic decay rates. Time Reversal symmetry is directly probed for the first time by the difference between the rates of $\overline{\mathrm{K}}^0 \to \mathrm{K}^0$ and $\mathrm{K}^0 \to \overline{\mathrm{K}}^0$, as measured in two of the semileptonic decay channels. CPLEAR results are summarized in the present paper.

We recall that antiprotons from the Low Energy Antiproton Ring (LEAR) were stopped in a hydrogen target at high pressure and annihilated with protons. The neutral kaons were produced through the so-called ‘golden channels’

$$\mathrm{p}\overline{\mathrm{p}} \;\to\; \begin{array}{l}\mathrm{K}^-\pi^+\mathrm{K}^0\\ \mathrm{K}^+\pi^-\overline{\mathrm{K}}^0\end{array}$$

with a branching ratio of $\approx 2\times10^{-3}$ for each channel. Since strong interactions conserve strangeness, it is clear that at production time the neutral kaon and the charged one have opposite strangeness, thus permitting the tagging of the neutral kaon. Detailed information on the CPLEAR detector can be found in reference [2].

2. Semileptonic decays

There are four possible semileptonic decays of the neutral kaons, two of them being allowed by the $\Delta S = \Delta Q$ rule and the two being forbidden. The decay rates are:

$$\begin{aligned}
R^+(t) &= R(\mathrm{K}^0{}_{t=0} \to \pi^-\mathrm{e}^+\nu)\\
R^-(t) &= R(\mathrm{K}^0{}_{t=0} \to \pi^+\mathrm{e}^-\overline{\nu})\\
\overline{R}^+(t) &= R(\overline{\mathrm{K}}^0{}_{t=0} \to \pi^-\mathrm{e}^+\nu)\\
\overline{R}^-(t) &= R(\overline{\mathrm{K}}^0{}_{t=0} \to \pi^+\mathrm{e}^-\overline{\nu})
\end{aligned}$$

Assuming that the $\Delta S = \Delta Q$ rule holds, the first and the fourth process are the ones which are directly allowed, whereas the second and the third may take place only after a $\Delta S = 2$ transition. The four decay rates may thus be written as:

$$\begin{aligned}
R^+(t) &= R[\mathrm{K}^0{}_{t=0} \to \mathrm{K}^0(t)]\\
R^-(t) &= R[\mathrm{K}^0{}_{t=0} \to \overline{\mathrm{K}}^0(t)]\\
\overline{R}^+(t) &= R[\overline{\mathrm{K}}^0{}_{t=0} \to \mathrm{K}^0(t)]\\
\overline{R}^-(t) &= R[\overline{\mathrm{K}}^0{}_{t=0} \to \overline{\mathrm{K}}^0(t)]
\end{aligned}$$

The asymmetry

$$A_T(t) \;=\; \frac{\overline{R}^+(t) - R^-(t)}{\overline{R}^+(t) + R^-(t)}$$

measures the difference between the probability of an initial K^0 being a $\overline{\mathrm{K}}^0$ at time t and the probability of an initial $\overline{\mathrm{K}}^0$ being a K^0 again at time t, hence the amount of T violation (fig. 1) (for a full discussion of the related phenomenology see [3], [4]).

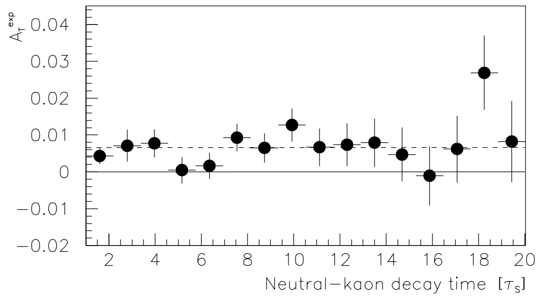

Figure 1: The $A_T^{exp}(t)$ asymmetry (τ_S is the $\mathrm{K_S}$ lifetime).

The data were corrected with respect to detection efficiencies and regeneration effects. The decay time resolution was folded to the fitting function. The main background source is the two-pion decays of neutral kaons, limited at early decay times. At late decay times there are contributions from three-pion decays and from semileptonic decays with reversed pion and electron assignment. The background contribution is nearly negligible in the total error.

The experimental result for the asymmetry is

$$A_T^{exp} = (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \times 10^{-3}$$

and it is the first direct measurement of Time Reversal violation [3].

From the semileptonic decays, other parameters may also be measured through the asymmetry $A_\delta^{exp}(t)$ (fig. 2), such as $Re(\delta)$, $Im(\delta)$ (which are CPT violating) and $Re(x_-)$ and $Im(x_+)$ (which are connected to the $\Delta S = \Delta Q$ rule, with x_- also CPT-violating) [5]. The values obtained, free of assumptions, are:

$$\begin{aligned} Re(\delta) &= (3.0 \pm 3.3_{stat} \pm 0.6_{syst}) \times 10^{-4}, \\ Im(\delta) &= (-1.5 \pm 2.3_{stat} \pm 0.3_{syst}) \times 10^{-2}, \\ Re(x_-) &= (0.2 \pm 1.3_{stat} \pm 0.3_{syst}) \times 10^{-2}, \\ Im(x_+) &= (1.2 \pm 2.2_{stat} \pm 0.3_{syst}) \times 10^{-2}, \end{aligned}$$

with correlation coefficients as given in [5]. Assuming that the $\Delta S = \Delta Q$ rule holds, then $Re(x_-) = Im(x_+) = 0$ and the analysis yields

$$\begin{aligned} Re(\delta) &= (2.9 \pm 2.6_{stat} \pm 0.6_{syst}) \times 10^{-4}, \\ Im(\delta) &= (-0.9 \pm 2.9_{stat} \pm 1.0_{syst}) \times 10^{-3} \end{aligned}$$

These values improve the limits obtained by a reanalysis of two previous experiments [6] by two and one orders of magnitude respectively.

The final results of the CPLEAR analysis, assuming only unitarity, through the Bell–Steinberger relation, and using recent CPLEAR and PDG values [7] improve further the limits for the parameters mentioned above [8].

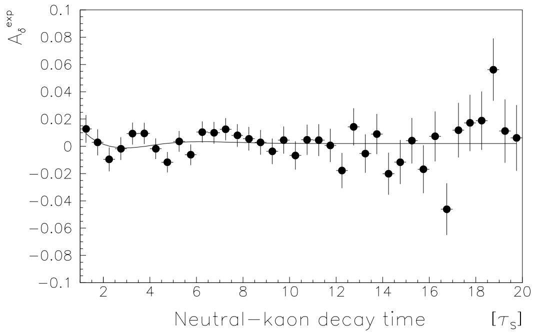

Figure 2: The $A_\delta^{exp}(t)$ asymmetry.

The asymmetry

$$A_{\Delta m}(t) = \frac{\overline{R}^-(t) + R^+(t) - \overline{R}^+(t) - R^-(t)}{\overline{R}^-(t) + R^+(t) + \overline{R}^+(t) + R^-(t)}$$

is a function of Δm and $Re(x)$. From this asymmetry (fig. 3), assuming no CPT-violating decay amplitudes, we obtain [9]:

$$\begin{aligned} \Delta m &= (0.5295 \pm 0.0020_{stat} \pm 0.0003_{syst}) \times 10^{10}\, \hbar s^{-1} \\ Re(x) &= (-1.8 \pm 4.1_{stat} \pm 4.5_{syst}) \times 10^{-3} \end{aligned}$$

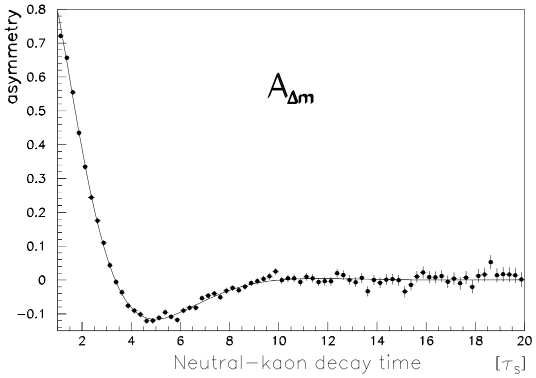

Figure 3: The $A_{\Delta m}(t)$ asymmetry for $\pi e \nu$ decays.

3. $\pi^+\pi^-$ decays

The differences in the decay rates of the CP conjugates K^0 and $\overline{K}^0$ to two charged pions is a sign of CP violation. In fig 4, these decay rates, corrected for the acceptance, are shown separately, for K^0 and $\overline{\mathrm{K}}^0$ initially tagged. The difference in the time dependence of the decay rates demonstrates the CP violation effect.

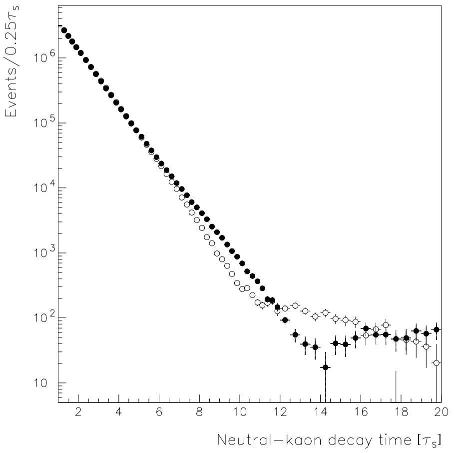

Figure 4: Neutral kaon decay to $\pi^+\pi^-$: the decay rates of $\overline{\mathrm{K}}^0$ (●) and K^0 (○) are shown separately.

By forming the time-dependent asymmetry

$$\begin{aligned} A_{+-}(t) &= \frac{R_{\overline{K}^0\to\pi^+\pi^-}(t) - \alpha R_{K^0\to\pi^+\pi^-}(t)}{R_{\overline{K}^0\to\pi^+\pi^-}(t) + \alpha R_{K^0\to\pi^+\pi^-}(t)} \\ &= -2\frac{|\eta_{+-}| e^{\frac{1}{2}(\Gamma_S-\Gamma_L)t}\cos(\Delta m\ t - \phi_{+-})}{1+|\eta_{+-}|^2 e^{(\Gamma_S-\Gamma_L)t}} \end{aligned}$$

the acceptances common to K^0 and $\overline{\mathrm{K}}^0$ cancel and the systematic uncertainties reduce accordingly. The normalization factor α includes the difference in the tagging efficiencies of K^{0}and $\overline{\mathrm{K}}^0$, which is a reflection of the the different detection efficiencies of the pairs K$^+\pi^-$ and K$^-\pi^+$ used to tag K^0 and $\overline{\mathrm{K}}^0$, see [10] . The asymmetry is shown in fig. 5 and it is fitted for $|\eta_{+-}|$, ϕ_{+-} and α. The data are corrected, event by event, for regeneration effects. Since there were no data available for the difference between the forward scattering amplitudes of K^0 and $\overline{\mathrm{K}}^0$ in the hundreds of MeVs energy region, dedicated runs were performed during the last year of operation of the CPLEAR detector [11].

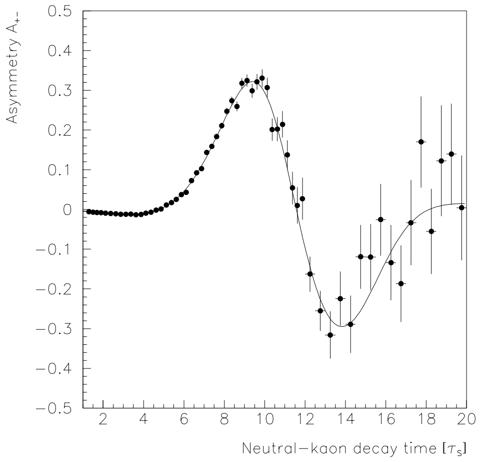

Figure 5: Neutral kaon decay to $\pi^+\pi^-$: the decay rate asymmetry A$_{+-}$ after background subtraction.

With

$$\Delta m = (530.1 \pm 1.4) \times 10^7\, \hbar s^{-1}$$

and

$$\tau_S = (89.32 \pm 0.08) psec$$

[7] the fit gives [10]:

$$\begin{aligned} |\eta_{+-}| = (2.264\ &\pm\ 0.023_{stat} \pm 0.026_{syst} \\ &\pm\ 0.007_{\tau_S}) \times 10^{-3}\ , \end{aligned}$$

$$\phi_{+-} = 43.19^0 \pm 0.53^0_{stat} \pm 0.28^0_{syst} \pm 0.42^0_{\Delta m}\ .$$

4. Summary

The first direct observation of T violation and tests of CPT invariance in K$^0-\overline{\mathrm{K}}^0$ mixing are reported. Measurements of other symmetry violating parameters are also reported, such as $|\eta_{+-}|$, ϕ_{+-} and the ones related to the $\Delta S = \Delta Q$ rule, as well as a measurement of Δm. In all cases the previous experimental values were improved by CPLEAR.

References

[1] E. Gabathuler and P. Pavlopoulos, Strong and weak CP violation at LEAR, Proceedings of the Workshop on physics at LEAR with low energy cooled antiprotons (Erice, 1982), ed. U. Gastaldi and R. Klapish (Plenum, New York, 1984) p.747.

[2] R. Adler et al., CPLEAR Collaboration, Nuclear Instruments and Methods A 379 (1996) 76.

[3] A. Angelopoulos et al., CPLEAR Collaboration, Phys. Lett. B 444 (1998) 43.

[4] L. Alvarez-Gaumé et al., CERN-TH/99-80, Phys. Lett. B, in print.

[5] A. Angelopoulos et al., CPLEAR Collaboration, Phys. Lett. B 444 (1998) 52.

[6] V.Demidov et al., Phys. Atom. Nucl. 58 (1995) 968.

[7] C. Caso et al., Particle Data Group, Eur. Phys. J. C 3 (1998) 1.

[8] A.Apostolakis et al., CPLEAR Collaboration, CERN-EP/99-51, Phys. Lett. B, in print.

[9] A. Angelopoulos et al., CPLEAR Collaboration, Phys. Lett. B 444 (1998) 38.

[10] A.Apostolakis et al., CPLEAR Collaboration, CERN-EP/99-65, Phys. Lett. B, in print.

[11] A. Angelopoulos et al., CPLEAR Collaboration, Phys. Lett. B 413 (1997) 422.