CP, T and CPT at CPLEAR

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Using strangeness tagging at production time, CPLEAR measures time-dependent decay rate asymmetries between K^0 and $\overline{\mathrm{K}}^0$, for pionic and semileptonic decays. Parameters describing CP, T, and CPT violation can be obtained with high precision. In the semileptonic channels neutral kaons are strangeness tagged also at the decay time, by the lepton charge, thus allowing the difference between the transition rates of $\overline{\mathrm{K}}^0 \to \mathrm{K}^0$ and $\mathrm{K}^0 \to \overline{\mathrm{K}}^0$ to be measured. In this way CPLEAR obtains the first direct measurement of T violation. By fitting the semileptonic rates under the constraint of the unitarity relation, we prove that in the reported measurement T violation is not mocked by CPT-violation effects in the decay amplitudes. Other CPLEAR measurements, only in part reported here, contribute to the experimental accuracy of the unitarity relation.

1 Introduction

The neutral-kaon system is a unique environment to test discrete symmetries (CP, T, CPT) to a high precision. The aim of the CPLEAR experiment is to study these symmetries by comparing K^0 and $\overline{K}^0$ decay rates for various decay channels. We note that although CP violation had been measured more than thirty years ago [1], a direct observation of T violation could only be achieved by the CPLEAR experiment with the use of pure K^0 and $\overline{K}^0$ sources. At the same time $K_S K_L$ interference could be measured in K^0, $\overline{K}^0$ decay rates in an optimal way. Neutral kaons were produced by an intense $\bar{p}$ beam through annihilations at rest,

$$\bar{p}p \to K^0 K^- \pi^+ \text{ and } \bar{p}p \to \overline{K}^0 K^+ \pi^-, \tag{1}$$

each channel having a branching ratio of $\approx 2 \times 10^{-3}$, and were strangeness-tagged, event by event, with the charge sign of the accompanying charged kaon.

The experimental apparatus is described elsewhere [2]. By measuring tracks, charge sign and momenta of primary particles, from annihilation, and secondary products, from neutral-kaon decay, one can select the decay channel, determine the decay time τ and study asymmetries between the decay rates Rs, such as

$$A_f(\tau) = \frac{R(\overline{K}^0 \to \bar{f},\ \tau) - R(K^0 \to f,\ \tau)}{R(\overline{K}^0 \to \bar{f},\ \tau) + R(K^0 \to f,\ \tau)} \tag{2}$$

where f is a specific final state and $\bar{f}$ its charge conjugate. In total, about 10^8 K^0 and $\overline{K}^0$ decays were reconstructed. The results presented here refer to the complete data-set of K^0, $\overline{K}^0$ decays to $\pi^+\pi^-$ (7×10^7) and to $e\pi\nu$ (1.3×10^6) in the interval $(1-20)\tau_S$ ($\tau_S \equiv K_S$ mean life) extracted from 5×10^4 data tapes, 10^5 events each.

2 $\pi^+\pi^-$ Decays

Decays to $\pi^+\pi^-$ are selected and fully reconstructed through a geometrical and kinematical constrained fit, resulting in a low background/signal ratio in the relevant lifetime interval. An asymmetry is then formed between the measured number of K^0 and $\overline{K}^0$ decaying to $\pi^+\pi^-$, $N(\tau)$ and $\bar{N}(\tau)$ respectively,

$$A_{+-}(\tau) = \frac{\bar{N}(\tau) - \alpha N(\tau)}{\bar{N}(\tau) + \alpha N(\tau)} = \frac{-2|\eta_{+-}|\cos(\Delta m\tau - \phi_{+-})e^{1/2(\Gamma_S - \Gamma_L)\tau}}{1 + |\eta_{+-}|^2 e^{(\Gamma_S - \Gamma_L)\tau}} \tag{3}$$

The r.h.s. of Eq. (3) is a function of the CP-violation parameter $\eta_{+-} = |\eta_{+-}|e^{\phi_{+-}}$ and of the K_L and K_S mass and decay-width difference, $\Delta m = m_L - m_S$ and $\Delta\Gamma = \Gamma_S - \Gamma_L$, respectively.

The normalization factor

$$\alpha = [1 + 4\mathrm{Re}(\epsilon - \delta)] \times \xi \text{ with } \xi = \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)\ , \tag{4}$$

corrects for the slight difference in the two decay rates due to the parameter $\epsilon_L = \epsilon - \delta$, as well as for the tagging/detection efficiency ξ of $\overline{K}^0$ relative to K^0. The parameters ϵ and δ describe CP/T and CP/CPT violation, respectively, in the neutral-kaon mixing matrix.

The use of this asymmetry makes the measurement, to the first order, independent of absolute acceptances and therefore of the Monte Carlo simulation, thus reducing systematic uncertainties. The dependence of ξ on the decay time is removed by constructing a multi-dimensional table of event weights in the relevant variables of the primary $K^\pm\pi^\mp$ kinematics. The table is constructed using events at short decay times where high statistics are available and CP-violation effects are small. Following this weighting procedure, the residual normalization factor α is expected to be equal to unity, when CP violation at short decay times is correctly taken into account. The value of α is left free in the fit of Eq. (3) to the data over the whole measured decay time range; the value returned by the fit is 0.9997 ± 0.0004.

Equation (3) is fitted to the measured asymmetry, shown in Fig. 1 after background subtraction, leaving $|\eta_{+-}|$, ϕ_{+-} and α as free parameters while fixing Δm, Γ_S and Γ_L to the PDG's fitted values[3]. The final results are[4]

$$\begin{aligned} |\eta_{+-}| &= (2.264 \pm 0.023_{stat} \pm 0.026_{syst} \pm 0.007_{\tau_S}) \times 10^{-3} \,, \\ \phi_{+-} &= 43.19^\circ \pm 0.53_{stat} \pm 0.28^\circ_{syst} \pm 0.42^\circ_{\Delta m}. \end{aligned}$$

Background level uncertainty, cut dependence and decay-time resolution are the main sources of systematic error, together with the residual uncertainty on regeneration effects.

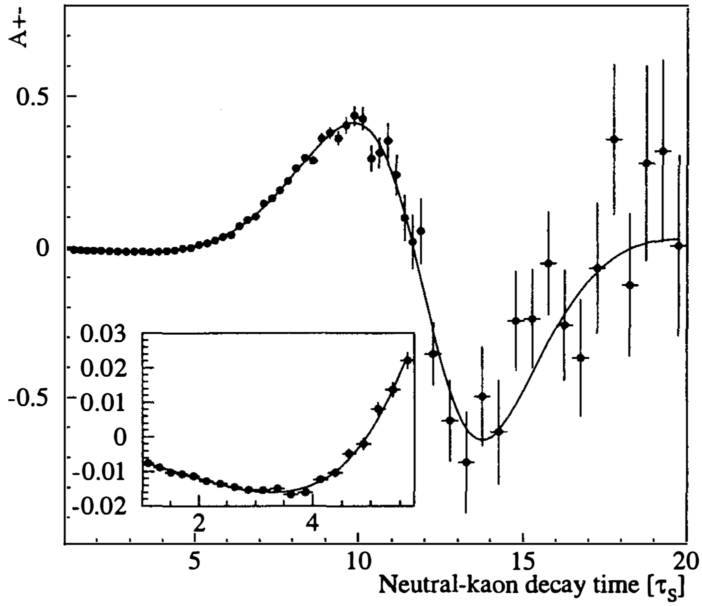

Figure 1: The time-dependent asymmetry $A_{+-}(\tau)$. The solid line is the result of the fit. The insert shows the data with a refined binning.

3 $e\pi\nu$ Decays

Reconstruction of decays to $e\pi\nu$ requires similar criteria as described in Section 2 and, in addition, that the electrons be identified by energy-loss and time-of-flight measured in scintillators and Cherenkov detectors. There are four measurables decay rates, labeled by kaon strangeness and electron charge,

$$\begin{aligned} R_+(\tau) &\equiv R\left[\mathrm{K^0}_{t=0} \to \mathrm{e}^+\pi^-\nu_{t=\tau}\right], & \overline{R}_-(\tau) &\equiv R\left[\overline{\mathrm{K}}^0{}_{t=0} \to \mathrm{e}^-\pi^+\overline{\nu}_{t=\tau}\right], \\ R_-(\tau) &\equiv R\left[\mathrm{K^0}_{t=0} \to \mathrm{e}^-\pi^+\overline{\nu}_{t=\tau}\right], & \overline{R}_+(\tau) &\equiv R\left[\overline{\mathrm{K}}^0{}_{t=0} \to \mathrm{e}^+\pi^-\nu_{t=\tau}\right]. \end{aligned}$$

The decay amplitudes are parametrized with quantities which have well defined symmetry properties under T, CP and CPT symmetries,

$$\begin{aligned} \langle \mathrm{e}^+\pi^-\nu|\, T\, |\mathrm{K^0}\rangle &= a + b\,, & \langle \mathrm{e}^-\pi^+\overline{\nu}|\, T\, |\overline{\mathrm{K}}^0\rangle &= a^* - b^*\,, \\ \langle \mathrm{e}^-\pi^+\overline{\nu}|\, T\, |\mathrm{K^0}\rangle &= c + d\,, & \langle \mathrm{e}^+\pi^-\nu|\, T\, |\overline{\mathrm{K}}^0\rangle &= c^* - d^*\,. \end{aligned} \tag{5}$$

Re(a) is CP, T and CPT symmetric, while the imaginary parts are all T-violating and $y = -b/a$ violates CPT. The parameters $x = (c^* - d^*)/(a + b)$ and $\bar{x} = (c^* + d^*)/(a - b)$, or $x_+ = (x + \bar{x})/2$ and

$x_- = (x - \bar{x})/2$, account for $\Delta S = \Delta Q$ rule breaking with x_- also violating CPT and $x_+ \leq 10^{-6}$ in the Standard Model.

The measured numbers of events, $N_\pm$ and $\overline{N}_\pm$ enter various asymmetries [5,6,7] where the common acceptance factors cancel. However we have to correct for the relative $\overline{\mathrm{K}}^0$ to K^0 tagging efficiency on production and decay side, ξ (see Section 2) and $\eta = \epsilon(\mathrm{e}^-\pi^+)/\epsilon(\mathrm{e}^+\pi^-)$.

An event-by-event correction was applied according to the $(\mathrm{e}^\pm\pi^\mp)$ kinematics. Calibration data were used to obtain η in bins of $p(\mathrm{e}, p_\pi)$. Its average value is $\langle\eta\rangle = 1.014 \pm 0.002$. An event-by-event correction was applied as well, according to the $(\mathrm{K}^\pm\pi^\mp)$ kinematics and using similar weight tables as in the two-pion case. However, these tables do not give directly ξ, but rather the quantity $\alpha_{2\pi} = [1 + 4\mathrm{Re}(\epsilon - \delta)] \times \xi$. If one needs ξ (as in the T-violation analysis) external information should be taken on $\mathrm{Re}(\epsilon - \delta)$ from the semileptonic charge asymmetry [3]

$$\delta_\ell = 2\mathrm{Re}(\epsilon - \delta) - 2\mathrm{Re}(x_- + y) = (3.27 \pm 0.12) \times 10^{-3},$$

which is equal to $2\mathrm{Re}(\epsilon - \delta)$ in the limit of CPT symmetry in semileptonic decays. In this limit, when averaging over the whole sample of semileptonic decays we estimate $\langle\xi\rangle = 1.12023 \pm 0.00043$.

Because of its construction the measurement of the asymmetry

$$A_{\Delta\mathrm{m}}(\tau) = \frac{(R_+ + \overline{R}_-) - (R_- + \overline{R}_+)}{(R_+ + \overline{R}_-) + (R_- + \overline{R}_+)}$$

depends only weakly on η and ξ. With the assumption of no CPT violation in possible $\Delta Q \neq \Delta S$ transitions ($x_- = 0$, $x_+ = x$) it is also

$$A_{\Delta\mathrm{m}}(\tau) = \frac{2\cos(\Delta m\tau)\mathrm{e}^{-1/2(\Gamma_\mathrm{S}+\Gamma_\mathrm{L})\tau}}{(1 + 2\mathrm{Re}(x))\mathrm{e}^{-\Gamma_\mathrm{S}\tau} + (1 - 2\mathrm{Re}(x))\mathrm{e}^{-\Gamma_\mathrm{L}\tau}} \; . \tag{6}$$

A measurement of Δm is performed by fitting Eq. (6) to data. The complete data-set is shown in Fig. 2 together with the result of the fit. The fit yields [5]

$$\begin{aligned} \Delta\mathrm{m} &= (529.5 \pm 2.0_{stat} \pm 0.3_{syst}) \times 10^7 \hbar s^{-1} \; , \\ \mathrm{Re}(x) &= (-1.8 \pm 4.1_{stat} \pm 4.5_{syst}) \times 10^{-3} \; . \end{aligned}$$

This represents the most precise single measurement of Δm; the error of $\mathrm{Re}(x)$ decreases by a factor of 3 with respect to the world average [3].

4 T and CPT Violation

The measurement of the quantity

$$A_\mathrm{T} = \frac{R(\overline{\mathrm{K}}^0 \to \mathrm{K}^0) - R(\mathrm{K}^0 \to \overline{\mathrm{K}}^0)}{R(\overline{\mathrm{K}}^0 \to \mathrm{K}^0) + R(\mathrm{K}^0 \to \overline{\mathrm{K}}^0)} \tag{7}$$

allows the time-reversal (T) symmetry to be directly tested [8]. With the measured number of events corrected by ξ and η CPLEAR has obtained [6]

$$A_\mathrm{T}(\tau) = \frac{\eta\overline{N}_+ - \xi N_-}{\eta\overline{N}_+ + \xi N_-} \tag{8}$$

The experimental asymmetry from the complete data-set with 6.4×10^5 events is shown in Fig. 3 where a non-zero level is clearly seen. Its average value

$$\langle A_\mathrm{T}^{exp}\rangle_{(1-20)\tau_\mathrm{S}} = (6.6 \pm 1.3_{stat} \pm 1.0_{syst}) \times 10^{-3} \; .$$

represents the first direct measurement of T violation in the limit of CPT-symmetric semileptonic decay amplitudes. The statistical significance of this measurement exceeds four standard deviations.

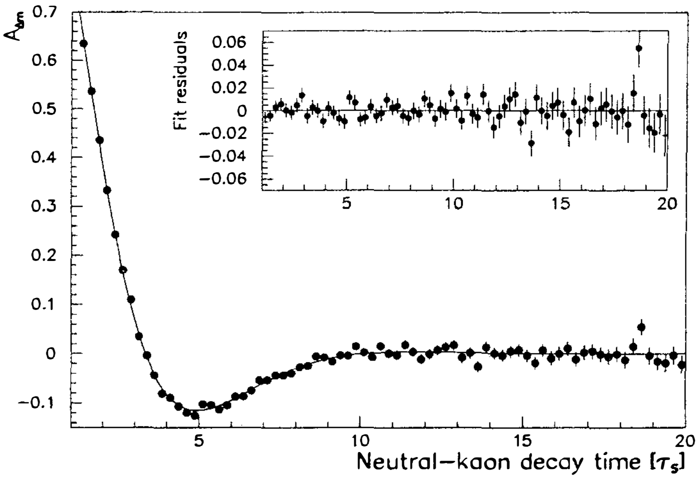

Figure 2: The time-dependent asymmetry $A_{\Delta m}(\tau)$. The solid line is the result of the fit. The insert shows the fit residuals.

The theoretical background and interpretation of the CPLEAR result is discussed elsewhere[9]. Here we recall that with the transition $\alpha_{2\pi} \longrightarrow \xi$ by using δ_ℓ, an additional term $-2\mathrm{Re}(x_- + y)$ enters into the phenomenological expression of A_{T}^{exp} which in the long lifetime limit becomes

$$A_{\mathrm{T}}^{exp} \underset{\tau \gg \tau_S}{\longrightarrow} 4\mathrm{Re}(\epsilon) - 4\mathrm{Re}(x_- + y). \tag{9}$$

Equation (9) suggests that the measured asymmetry A_{T}^{exp} could arise either from T violation in the mixing or/and from CPT violation in the decay amplitudes. However, taking into account the whole of the information on the neutral-kaon system (see below) CPLEAR has concluded that the term $\mathrm{Re}(x_- + y)$ can safely be neglected.

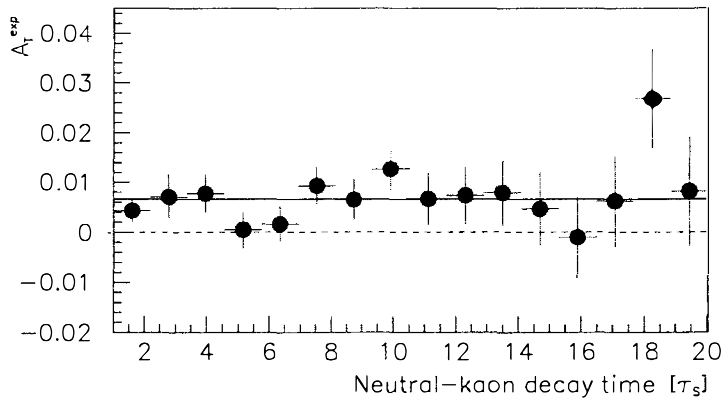

Figure 3: The T-violation asymmetry A_{T}^{exp} versus the neutral-kaon decay time. The solid line shows the result of the fit with a constant ($\langle A_{\mathrm{T}}^{exp}\rangle$).

CPT violation in mixing is tested directly through the asymmetry[7]

$$A_\delta(\tau) = \frac{\eta \overline{N}_+ - \alpha_{2\pi} N_-}{\eta \overline{N}_+ + \alpha_{2\pi} N_-} + \frac{\overline{N}_- - \eta\alpha_{2\pi} N_+}{\overline{N}_- + \eta\alpha_{2\pi} N_+}. \tag{10}$$

Since this asymmetry is constructed with $\alpha_{2\pi}$ instead of ξ, in its phenomenological expression the factor $[1+4\mathrm{Re}(\epsilon-\delta)]$ leads to a cancellation of terms containing $\mathrm{Re}(\epsilon)$ and $\mathrm{Re}(y)$. In the long lifetime limit the expression simplifies to

$$A_\delta \underset{\tau\gg\tau_S}{\longrightarrow} 8\mathrm{Re}(\delta). \tag{11}$$

Fitting the A_δ data with the complete phenomenological expression, which depends on $\mathrm{Re}(\delta)$, $\mathrm{Im}(\delta)$, $\mathrm{Im}(x_+)$ and $\mathrm{Re}(x_-)$, yields

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

with large correlation coefficients between $\mathrm{Im}(\delta)$, $\mathrm{Im}(x_+)$ and $\mathrm{Re}(x_-)$. If we assume the validity of the $\Delta S = \Delta Q$ rule, $\mathrm{Re}(x_-) = \mathrm{Im}(x_+) = 0$, the error on $\mathrm{Im}(\delta)$ and $\mathrm{Re}(\delta)$ decreases by one order of magnitude and 25%, respectively, which represents an improvement by a factor 12 and 75 when compared to previous measurements under the same assumptions [3].

Finally, a global fit of the semileptonic data under the constraint of the Bell-Steinberger (unitarity) relation yields [10]

$$\begin{aligned}
\mathrm{Re}(\delta) &= (\ \ 2.4 \pm 2.8) \times 10^{-4}\ , \\
\mathrm{Im}(\delta) &= (\ \ 2.4 \pm 5.0) \times 10^{-5}\ , \\
\mathrm{Re}(\epsilon) &= (\ \ 164.9 \pm 2.5) \times 10^{-5}\ , \\
\mathrm{Re}(y) &= (\ \ 0.3 \pm 3.1) \times 10^{-3}\ , \\
\mathrm{Re}(x_-) &= (-0.5 \pm 3.0) \times 10^{-3}\ , \\
\mathrm{Im}(x_+) &= (-2.0 \pm 2.7) \times 10^{-5}\ .
\end{aligned}$$

The parameters $\mathrm{Re}(y)$ and $\mathrm{Re}(x_-)$ have a strong negative correlation; the sum, which enters Eq. (9), is therefore given with a smaller error than the individual terms,

$$\mathrm{Re}(x_- + y) = (-0.2 \pm 0.3) \times 10^{-3}\ .$$

This result, based on measured values and the sole assumption of unitarity, confirms the interpretation of A_{T}^{exp} as a direct measurement of time-reversal violation.

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