RESULTS FROM CPLEAR*

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The CPLEAR experiment measures CP-, T-, and CPT-symmetries in the neutral kaon system. For the first time, T-violation and CPT-conservation is measured by a direct method using semileptonic decays. The limit on the CPT-violation parameter $\mathrm{Re}\,(\delta)$ is improved by two orders of magnitude as compared to previous measurements. An indirect test of CPT symmetry is performed using the Bell–Steinberger relation and CPLEAR results, improving the current limits on $\mathrm{Re}\,(\varepsilon)$ and $\mathrm{Im}\,(\delta)$ by almost one order of magnitude.

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1. Introduction

At present, the neutral-kaon system remains the laboratory for measuring with high precision the set of parameters which describe, in the most general way, the discrete symmetries CP, T and CPT. CPLEAR has successfully developed a novel experimental approach [1] to measure these parameters. The method is based on the measurement of time-dependent decay-rate asymmetries for the main decay modes, between particles (K^0) and antiparticles ($\overline{K}^0$). The strangeness of the neutral kaons decaying in the range $0 < \tau < 20\,\tau_{\mathrm{S}}$, is tagged at the time of production and of decay (for the semileptonic decay). This tagging capability at production and decay time is specific of the CPLEAR experiment and enables us to perform a direct measurement of time reversal (T) non-invariance and of CPT-symmetry.

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2. Neutral-kaon phenomenology

The time evolution and decay of neutral kaons can be parameterized in terms of different, mostly equivalent, kaon-mixing and decay parameters. We briefly outline the parameterization used in our analysis [2, 3]. The two parameters which describe the neutral-kaon mixing are, respectively, the T- and CPT-violation parameters:

$$\varepsilon = \frac{\Lambda_{\overline{K}^0 K^0} - \Lambda_{K^0 \overline{K}^0}}{2(\lambda_\mathrm{L} - \lambda_\mathrm{S})} \qquad \text{and} \qquad \delta = \frac{\Lambda_{\overline{K}^0 \overline{K}^0} - \Lambda_{K^0 K^0}}{2(\lambda_\mathrm{L} - \lambda_\mathrm{S})} \,.$$

Here Λ_{ij} are the elements and $\lambda_\mathrm{S,L}$ the eigenvalues of the effective Hamiltonian $\Lambda \equiv \mathrm{M} - \frac{\mathrm{i}}{2}\Gamma$, $\lambda_\mathrm{S,L} = m_\mathrm{S,L} - \frac{i}{2}\Gamma_\mathrm{S,L}$ where $m_\mathrm{S,L}$ and $\Gamma_\mathrm{S,L}$ are the masses and decay widths for the K_S and K_L states. The K_S and K_L states are the eigenvectors of Λ. The semileptonic decays are described by four amplitudes:

$$\langle \ell^+\pi^-\nu|\Lambda|K^0\rangle = a + b\,, \qquad \langle \ell^-\pi^+\overline{\nu}|\Lambda|\overline{K}^0\rangle = a^* - b^*\,,$$
$$\langle \ell^-\pi^+\overline{\nu}|\Lambda|K^0\rangle = c + d\,, \qquad \langle \ell^+\pi^-\nu|\Lambda|\overline{K}^0\rangle = c^* - d^*\,.$$

The amplitudes b and d are CPT-violating, c and d describe possible violations of the $\Delta S = \Delta Q$ rule and the imaginary parts are all T-violating. The quantities $x = (c^* - d^*)/(a + b)$ and $\overline{x} = (c^* + d^*)(a - b)$ describe the violation of the $\Delta S = \Delta Q$ rule in decays into positive and negative leptons, respectively, while $y = -b/a$ describes CPT-violation in semileptonic decays in the case where the $\Delta S = \Delta Q$ rule holds. The parameters $x_+ = (x + \overline{x})/2$ and $x_- = (x - \overline{x})/2$ describe therefore the violation of the $\Delta S = \Delta Q$ rule in CPT-conserving and CPT-violating amplitudes, respectively.

3. CPLEAR method

The neutral kaons were produced in CPLEAR through the strong interactions $p\overline{p} \to K^-\pi^+K^0$ and $p\overline{p} \to K^+\pi^-\overline{K}^0$ where $p\overline{p}$ annihilate at rest. Full details of the design, operation and performance of the CPLEAR detector can be found in reference [4]. The CPLEAR experiment measures time-dependent decay-rates of initially-tagged neutral kaons. The strangeness of the neutral kaon at its creation is defined by the charge of the accompanying kaon (K^+ for $\overline{K}^0$, K^- for K^0). The decay volume of the CPLEAR detector covers the lifetime range of 0–20 τ_S. Final states f ($\pi^+\pi^-$, $\pi^0\pi^0$, $e\pi\nu$, $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$) are measured and identified, and physics parameters are extracted from time-dependent decay-rate asymmetries, such as the one shown for the two charged pions final state [5] in figure 1. These asymmetries have the advantage that the detection and reconstruction efficiencies, which

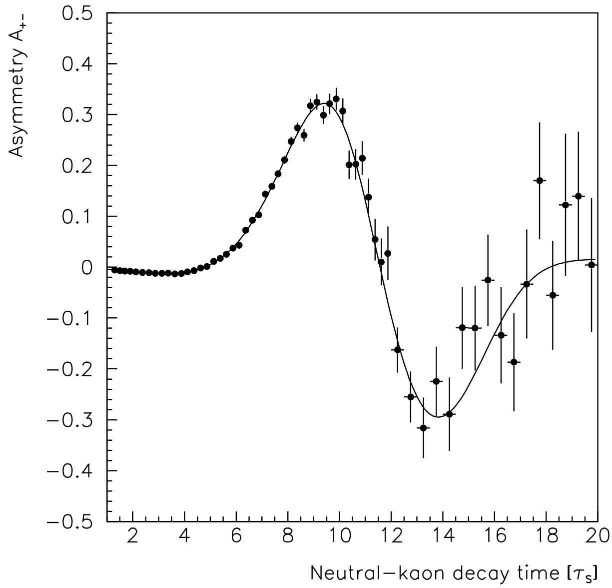

Fig. 1. The decay-rate asymmetry for neutral kaons decaying into two charged pions, as function of the neutral-kaon decay time (in units of τ_S).

are common to the different decays, cancel. However, the detection probabilities are not identical for opposite-charge kaons, pions and electrons which were used for tagging the strangeness of the neutral kaon at the production and at the decay time. Hence normalization factors were evaluated for both the primary (production) and the secondary (decay) vertices. Differences resulting from geometrical detector imperfections were reduced by reversing the magnetic field several times a day. To correct for neutral kaon regeneration in the detector material a dedicated run [6] was performed to obtain the forward scattering amplitude information in the momentum range of the experiment.

4. Measurements of T and CPT symmetry with K^0, $\overline{K}^0 \to e\pi\nu$

Among the highlights of the CPLEAR experiment are certainly the direct symmetry test of T and CPT-violation. Since weak interactions do not conserve strangeness, a K^0 meson can transform into a $\overline{K}^0$, and vice versa, a $\overline{K}^0$ can transform into a K^0. Time-reversal (T) invariance, or microscopic reversibility, would require all details of the second process to be deducible from the first; in particular, the probability that a $K^0(t = 0)$ is observed as a $\overline{K}^0$ at time τ should be equal to the probability that a $\overline{K}^0(t = 0)$ is observed as a K^0 at the same time τ. Any difference between these two probabilities is a signal for T violation [7]. Figure 2 shows the properly

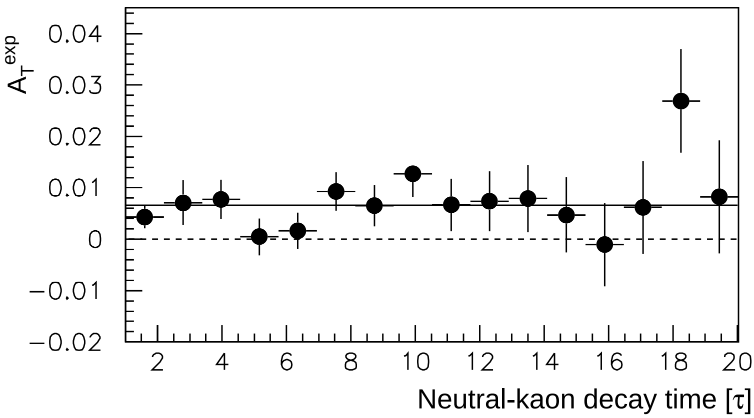

Fig. 2. The asymmetry $A_T^{\rm exp}(\tau)$ *versus* the neutral-kaon decay time (in units of $\tau_{\rm S}$). The solid line represents the result of the fit (see text).

normalized asymmetry that is measured by CPLEAR [8]:

$$A_T^{\rm exp}(\tau) = \frac{R(\overline{K}^0 \to e^+\pi^-\nu) - R(K^0 \to e^-\pi^+\overline{\nu})}{R(\overline{K}^0 \to e^+\pi^-\nu) + R(K^0 \to e^-\pi^+\overline{\nu})}\,.$$

For a large neutral-kaon decay time, the above asymmetry becomes a constant: $A_T^{\rm exp}(\tau \gg \tau_{\rm S}) = 4{\rm Re}\,(\varepsilon) - 4{\rm Re}\,(y + x_-)$. In the limit of CPT-symmetry in the semileptonic decay (${\rm Re}\,(y) = 0$ and $x_- = 0$) this is a direct measurement of T-violation, where we still allow for a possible violation of the $\Delta S = \Delta Q$ rule ($x_+ \neq 0$). The fitting procedure then contains the two parameters: $4{\rm Re}\,(\varepsilon) \equiv A_T^{\rm exp}(\tau \gg \tau_{\rm S})$ and ${\rm Im}\,(x_+)$. When fitting the asymmetry $A_T^{\rm exp}$ in the decay-time range of $1 - 20\ \tau_{\rm S}$, we obtain:

$$\begin{aligned} 4{\rm Re}\,(\varepsilon) &= (6.2 \pm 1.4_{\rm stat} \pm 1.0_{\rm syst}) \times 10^{-3}\,, \\ {\rm Im}\,(x_+) &= (1.2 \pm 1.9_{\rm stat} \pm 0.9_{\rm syst}) \times 10^{-3}\,. \end{aligned}$$

Similarly, the CPT-symmetry can be tested by measuring probabilities for K^0 and $\overline{K}^0$ being produced and decaying with the same strangeness. The probability that a $K^0(t = 0)$ is observed as a K^0 at time τ should be equal to the probability that a $\overline{K}^0(t = 0)$ is observed as a $\overline{K}^0$ at the same time τ. From the point of view of systematic errors (normalization uncertainties) it is favorable to consider an appropriate asymmetry function $A_\delta^{\rm exp}$ of all four rates [9]. The asymmetry becomes a constant for large neutral-kaon decay times; $A_\delta^{\rm exp}(\tau \gg \tau_{\rm S}) = 8{\rm Re}\,(\delta)$. Free from any assumptions on the validity of the $\Delta S = \Delta Q$ rule or on CPT-conservation in the semileptonic decays, the result of the fit in the decay-time range of 1–20 τ_{S} is:

$$\mathrm{Re}\,(\delta) = (3.0 \pm 3.3_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}}) \times 10^{-4}\,,$$

thus increasing the accuracy of this parameter by two orders of magnitude if compared with previous measurements [10].

5. An indirect test of *CPT*

The Bell–Steinberger relation [11], or unitarity relation, gives us the opportunity to determine the values of $\mathrm{Im}\,(\delta)$ and $\mathrm{Re}\,(\varepsilon)$:

$$\begin{aligned}\mathrm{Re}\,(\varepsilon) - \mathrm{i}\mathrm{Im}\,(\delta) \;=\; & \frac{1}{2(\mathrm{i}\Delta m + \frac{1}{2}\gamma)} \times \Big(\sum (|A_{\mathrm{S}}|^2 \eta_{\pi\pi}) + \sum (|A_{\mathrm{L}}|^2 \eta^*_{3\pi}) \\ & + 2[\mathrm{Re}\,(\varepsilon) - \mathrm{Re}\,(y) - \mathrm{i}(\mathrm{Im}\,(x_+) + \mathrm{Im}\,(\delta))] |f_{e\pi\nu}|^2 \Big)\,,\end{aligned}$$

with $\Delta m = m_{\mathrm{L}} - m_{\mathrm{S}}$, $\gamma = \Gamma_{\mathrm{S}} + \Gamma_{\mathrm{L}}$, $|A_{\mathrm{S}}|^2 = \mathrm{BR}\,(K_{\mathrm{S}} \to \pi\pi)\,\Gamma_{\mathrm{S}}$, $|A_{\mathrm{L}}|^2 = \mathrm{BR}\,(K_{\mathrm{L}} \to \pi\pi\pi)\,\Gamma_{\mathrm{L}}$, $|f_{e\pi\nu}|^2 = \mathrm{BR}\,(K_{\mathrm{L}} \to e\pi\nu)\,\Gamma_{\mathrm{L}}$. With additional constraints from A_T, A_δ and using the results from CPLEAR on CP-violation in two pions and three pions final states [5, 12, 13] together with PDG values [14], we obtain the following results [15]:

$$\begin{aligned}\mathrm{Re}\,(\varepsilon) &= (165.0 \pm 4.1) \times 10^{-5}\,,\\ \mathrm{Im}\,(\delta) &= (2.4 \pm 4.2) \times 10^{-5}\,,\\ \mathrm{Im}\,(x_+) &= (-2.2 \pm 2.7) \times 10^{-3}\,,\\ \mathrm{Re}\,(y) &= (0.4 \pm 3.1) \times 10^{-3}\,,\\ \mathrm{Re}\,(\delta) &= (2.4 \pm 2.8) \times 10^{-4}\,,\\ \mathrm{Re}\,(x_-) &= (-0.6 \pm 3.1) \times 10^{-3}\,.\end{aligned}$$

The parameters $\mathrm{Re}\,(\varepsilon)$, $\mathrm{Re}\,(y)$ and $\mathrm{Re}\,(x_-)$ are independently evaluated for the first time, free from any assumptions on the validity of the $\Delta S = \Delta Q$ rule or on CPT-conservation in the semileptonic decays. The error on $\mathrm{Re}\,(\varepsilon)$ and $\mathrm{Im}\,(\delta)$ is dominated by the error on η_{000}. The CPLEAR accuracy on $\pi^+\pi^-\pi^0$ and on semileptonics are such that their contributions became negligible. If we assume that $\eta_{+-0} = \eta_{000}$, the errors on the parameters $\mathrm{Re}\,(\varepsilon)$ and $\mathrm{Im}\,(\delta)$ are reduced by a factor of two. The limit we obtain on the parameter $\mathrm{Im}\,(\delta)$ is by three orders of magnitude more accurate than the limit obtained by a re-analysis of two earlier experiments [10], and our results on $\mathrm{Re}\,(\varepsilon)$ and $\mathrm{Im}\,(\delta)$ are almost an order of magnitude more accurate than a previous similar analysis [16].

6. Conclusion

The CPLEAR Collaboration has performed the first direct measurement of T-reversal violation and CPT-invariance, the latter down to a level of $\sim 10^{-4}$. The results being in agreement with CPT-conservation show that CP-violation is associated to T-violation. Using the Bell–Steinberger relation and CPLEAR results, the current limits on $\mathrm{Re}\,(\varepsilon)$ and $\mathrm{Im}\,(\delta)$ are improved by almost one order of magnitude.

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