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Direct tests of T, CP, CPT symmetries in transitions of neutral kaons at KLOE

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A data sample of 1.7 fb^{-1} has been analyzed by the KLOE experiment at DAΦNE to study the distribution of the difference in the kaon decay times Δt, of $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^- \ \pi^\pm e^\mp \nu$ and $\phi \to \mathrm{K_S K_L} \to \pi^\pm e^\mp \nu \ \pi^0\pi^0\pi^0$. Tests of T, CP and CPT symmetries in the neutral kaon system are performed by direct comparison of the probabilities of a kaon transition process and the symmetry-conjugate transition. The exchange of *in* and *out* states required for genuine T and CPT tests is fulfilled exploiting the entanglement of kaon pairs produced at the ϕ-factory. We were able, by the comparison of the measured Δt distributions in the asymptotic region $\Delta t \gg \tau_S$, to directly test for the first time T and CPT symmetries in kaon transitions with a few percent precision and to observe CP violation in transitions from CP odd eigenstates to flavour eigenstates, K^0 and $\overline{K}^0$.

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1. Introduction

A genuine, direct test of T and CPT symmetries requires the measurement of transitions with initial and final states exchanged [1]. Initial and final state exchange is possible exploiting the maximal entanglement of meson–antimeson pairs, as $\mathrm{B}^0\overline{\mathrm{B}}^0$ produced at the B-factories and $\mathrm{K}^0\overline{\mathrm{K}}^0$ at the ϕ-factory. The methodology for testing T was developed in ref. [2] for the B^0-system and afterwards the BABAR Collaboration obtained the first direct observation of Time Reversal Violation, TRV [3] .

In this paper we present the results of the first direct T, CP and CPT tests performed in the $\mathrm{K}^0-\overline{\mathrm{K}}^0$ system according to the studies in refs.[4, 5], using data from the KLOE experiment. We have measured the transitions from (to) kaon CP eigenstates $K_{CP=-}$ and $K_{CP=+}$ to (from) kaon flavour eigenstates K^0 and $\overline{\mathrm{K}}^0$. In this work kaon CP parity is inferred from the 2-pion or 3-pion decay channel. The orthogonality condition $|\mathrm{K}^{\perp}_{\mathrm{CP}=\mp}\rangle = |\mathrm{K}_{\mathrm{CP}=\pm}\rangle$ holds when the CP parity is in the limit of negligible direct CP (and CPT) violation contributions, an assumption well satisfied by neutral kaons [5]. The second orthogonal basis is that of flavour eigenstates $|\mathrm{K}^0\rangle$ and $|\overline{\mathrm{K}}^0\rangle$. Orthogonality condition is in this case assured by the $\Delta S = \Delta Q$ rule [6], and we identify flavour eigenstates by the lepton charge of the kaon semileptonic decay, with $|\mathrm{K}^0\rangle$ decaying only into $\pi^-e^+\nu$ and $|\overline{\mathrm{K}}^0\rangle$ to $\pi^+e^-\overline{\nu}$.

Starting for example with the transition $\mathrm{K}^0(0) \to K_{CP=-}(t)$, we can consider:

the T-conjugate process $K_{CP=-}(0) \to \mathrm{K}^0(t)$

the CP-conjugate process $\overline{\mathrm{K}}^0(0) \to K_{CP=-}(t)$

the CPT-conjugate process $K_{CP=-}(0) \to \overline{\mathrm{K}}^0(t)$.

Initial states are tagged exploiting the maximal anti-symmetry of the kaon pairs produced at the ϕ-factory, $|i\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right) = \frac{1}{\sqrt{2}}\left(|K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle\right)$ so that $K_{CP=-}(0)$ is tagged by the measurement of $K^0_1 \to \pi^+\pi^-$ while $K_{CP=-}(t)$ is filtered by the measurement of $K^0_2 \to \pi^0\pi^0\pi^0$, where K_1 is the first kaon of the pair to decay and K_2 the second one. $\overline{\mathrm{K}}^0(0)$ is analogously tagged by the measurement of $K^0_1 \to \pi^-e^+\nu$ while $\overline{\mathrm{K}}^0(t)$ is filtered by the observation of $K^0_2 \to \pi^+e^-\overline{\nu}$. The transitions can be divided into four categories, corresponding to independent T, CP and CPT tests [5]. KLOE data belong to two of these categories. We can directly compare the probabilities of reference transitions with the conjugated transitions, and define the observables:

$$
\begin{aligned}
R^{exp}_{2,T}(\Delta t) &\equiv \frac{I(\pi^+e^-\overline{\nu},\pi^0\pi^0\pi^0;\Delta t)}{I(\pi^+\pi^-,\pi^-e^+\nu;\Delta t)} & R^{exp}_{4,T}(\Delta t) &\equiv \frac{I(\pi^-e^+\nu,\pi^0\pi^0\pi^0;\Delta t)}{I(\pi^+\pi^-,\pi^+e^-\overline{\nu};\Delta t)} \\
R^{exp}_{2,CP}(\Delta t) &\equiv \frac{I(\pi^+e^-\overline{\nu},\pi^0\pi^0\pi^0;\Delta t)}{I(\pi^-e^+\nu,\pi^0\pi^0\pi^0;\Delta t)} & R^{exp}_{4,CP}(\Delta t) &\equiv \frac{I(\pi^+\pi^-,\pi^-e^+\nu;\Delta t)}{I(\pi^+\pi^-,\pi^+e^-\overline{\nu};\Delta t)} \\
R^{exp}_{2,CPT}(\Delta t) &\equiv \frac{I(\pi^+e^-\overline{\nu},\pi^0\pi^0\pi^0;\Delta t)}{I(\pi^+\pi^-,\pi^+e^-\overline{\nu};\Delta t)} & R^{exp}_{4,CPT}(\Delta t) &\equiv \frac{I(\pi^-e^+\nu,\pi^0\pi^0\pi^0;\Delta t)}{I(\pi^+\pi^-,\pi^-e^+\nu;\Delta t)}
\end{aligned}
\tag{1}
$$

where $I(f_1, f_2;\Delta t)$ is the decay rate as a function of Δt, with f_1 decay preceding f_2 when $\Delta t > 0$. We have measured the asymptotic values of the ratios of the transitions rates, when $\Delta t \gg \tau_s$, that can be expressed using a parametrization [7] of the discrete-symmetries violating terms in the

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Weisskopf–Wigner effective Hamiltonian,

$$\begin{aligned}
\mathcal{N}\cdot R^{\rm exp}_{2,\rm T}(\Delta t\gg\tau_S) &= 1-4\Re\epsilon+\left(4\Re x_+ + 4\Re y\right)\\
\mathcal{N}\cdot R^{\rm exp}_{4,\rm T}(\Delta t\gg\tau_S) &= 1+4\Re\epsilon+\left(4\Re x_+ - 4\Re y\right)\\
R^{\rm exp}_{2,\rm CP}(\Delta t\gg\tau_S) &= 1-4\Re\epsilon_S+\left(4\Re y - 4\Re x_-\right)\\
R^{\rm exp}_{4,\rm CP}(\Delta t\gg\tau_S) &= 1+4\Re\epsilon_L-\left(4\Re y + 4\Re x_-\right)\\
\mathcal{N}\cdot R^{\rm exp}_{2,\rm CPT}(\Delta t\gg\tau_S) &= 1-4\Re\delta+\left(4\Re x_+ - 4\Re x_-\right)\\
\mathcal{N}\cdot R^{\rm exp}_{4,\rm CPT}(\Delta t\gg\tau_S) &= 1+4\Re\delta+\left(4\Re x_+ + 4\Re x_-\right)
\end{aligned}\tag{2}$$

where $\mathcal{N}=\frac{BR(K_S\to\pi^+\pi^-)\cdot\Gamma_S}{BR(K_L\to\pi^0\pi^0\pi^0)\cdot\Gamma_L}=(1.970\pm0.023)\,10^3$, τ_S is the K_S lifetime, ϵ and δ are the T and CPT violation parameters and $\epsilon_{S,L}=\epsilon\pm\delta$ are the CP-mixing parameters of the physical states, $\rm K_S$ and $\rm K_L$. The parameter y is the term giving CPT violation in the $\Delta S=\Delta Q$ semileptonic decay amplitudes, while x_+ and x_- give the $\Delta S\neq\Delta Q$ CPT-invariant and CPT-violating terms. The brackets on the right side of eqs.2 outline spurious effects appearing when our assumptions, i.e. $\Delta S=\Delta Q$ and absence of direct CP and CPT violation, are released. They turn out to be fully negligible in the asymptotic region $\Delta t\gg\tau_S$ [4, 5]. We have also measured the double ratios,

$$DR_{\rm T,CP} \equiv \frac{R_{2,\rm T}}{R_{4,\rm T}}\equiv\frac{R_{2,\rm CP}}{R_{4,\rm CP}}=1-8\Re\epsilon+\left(8\Re y\right)\tag{3}$$

$$DR_{\rm CPT} \equiv \frac{R_{2,\rm CPT}}{R_{4,\rm CPT}}=1-8\Re\delta-\left(8\Re x_-\right)\tag{4}$$

The double ratio (4) is the most robust of our observables. A value different from 1 can only arise from CPT violation, also in case the $\Delta S=\Delta Q$ rule is violated, being x_- itself a pure CPT-violating term.

2. Data Analysis

Reconstruction and selection of $\phi\to\rm K_SK_L\to\pi^\pm e^\mp\nu\ \ \pi^0\pi^0\pi^0$ and $\phi\to\rm K_SK_L\to\pi^+\pi^-\ \ \pi^\pm e^\mp\nu$ exploit the best features of the KLOE detector, i.e. excellent performance of the huge and light drift chamber (DC), giving a momentum resolution of $\frac{\Delta p_\perp}{p_\perp}\simeq0.4\%$, and the time resolution of the calorimeter (EMC), $\Delta T\simeq\frac{54ps}{\sqrt{E[GeV]}}$. Selection of $\phi\to K_1^0K_2^0\to\pi^\pm e^\mp\nu\ \ \pi^0\pi^0\pi^0$ is challenging because of the high rate of the dominant $K_1^0\to\pi^+\pi^-$ background. A vertex with two tracks of opposite charge is required in a cylindrical volume, with $\rho=\sqrt{x^2+y^2}<3$ cm and $|z|<4.5$ cm around the interaction point (IP), where z is the longitudinal and $x,\ y$ are the transverse coordinates. The invariant mass of the two tracks in the hypothesis of two charged pions is required to be outside the window of $\rm K_S\to\pi^+\pi^-$ decays, i.e. $m_{\pi\pi}>490$ MeV/c^2. A time of flight analysis of the tracks is then conducted to identify lepton charge and for improving on the rejection power of the $\rm K_S\to\pi^+\pi^-$ background. The tracks are extrapolated to the calorimeter and the difference $\delta t(m_X)$ between time of flight T as measured by the calorimeter and time expected from the track length L recostructed by the DC assuming particle mass m_X, are studied to discriminate among the different mass hypothesis. The distributions of $\delta t_1(m_\pi)=T_1-\frac{L_1}{c\,p_1}\sqrt{p_1^2+m_\pi^2}$ vs $\delta t_1(m_e)$ and $\delta t_2(m_\pi)$ vs

$\delta t_2(m_e)$ as well as the distribution of $d\delta t(m_\pi, m_e) = \delta t_1(m_\pi) - \delta t_2(m_e)$ vs $d\delta t(m_e, m_\pi)$ are used for the selection applying proper cuts [8]. The $\mathrm{K_L} \to \pi^0\pi^0\pi^0 \to 6\gamma$ vertex is selected by searching for six clusters in the calorimeter not associated to tracks in the DC, each with E > 20 MeV, a total energy from 350 to 700 MeV and invariant mass greater than 350 MeV/c^2. The decay vertex is reconstructed independently for each choice of four γs and the results are compared to identify photons not originating from the $\mathrm{K_L}$ decay point. If more than one set of six clusters satisfies the consistency cut, the set with the best matching of the decay positions is selected. Contamination does not exceed 2%, furtherly reduced by requiring at most one cluster with $R/(cT_{clu}) > 0.9$ where R is the distance from the IP. Residual background is largely dominated by $\pi^+\pi^-(\gamma)\ \ \pi^0\pi^0\pi^0$ events, with or without π^+/π^- decays in the DC, where a pion or muon track is misidentified as e^+/e^-. An Artificial Neural Networks (ANNs) classifier analysis has been exploited for e/π and μ/π discrimination, based on the different topology of the energy deposited in the EMC cells, in combination with particle momenta measured by the DC. The ANNs are trained using data control samples of $\mathrm{K_L} \to \pi^\pm e^\mp \nu$ and $\mathrm{K_L} \to \pi^\pm \mu^\mp \nu$ tagged by $\mathrm{K_S} \to \pi^+\pi^-$. The analysis leads to a signal-to-background ratio of 22.5. The distribution of the residual background as a function of Δt is modelled with an exponential function that has been used to subtract the contamination from data distributions.
The $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\ \ \pi^\pm e^\mp \nu$ is easier to be identified. Main issue in this case is the separation of the $K_2^0 \to \pi^+\pi^-\pi^0$ and $K_2^0 \to \pi\mu\nu$ channels. Event selection requires the presence of a DC vertex associated to two opposite curvature tracks within a cylindrical volume of $\rho < 15$ cm and $|z| < 10$ cm around the IP and with $|m_{\pi\pi} - m_{\mathrm{K^0}}| < 10$ MeV/c^2. All vertices formed by two opposite curvature tracks in the DC are then considered to identify the semileptonic decay, after exclusion of those tracks associated with the $\mathrm{K_S} \to \pi^+\pi^-$ vertex. For each candidate semileptonic vertex the cut $(E_+^2 + E_-^2) - (p_+^2 + p_-^2) < 0.015\ (\,GeV/c^2\,)^2$ is applied, where $E_\pm = E_K - E(\pi_\mp) - p_{miss}$. One of the invariant masses in the sum should correspond to the electron mass when the e/π identification is correct, and the background events peak to larger values of the sum [8]. Further selection of semileptonic decays of $\mathrm{K_L}$ as well as identification of the $e^\pm$ and $\pi^\pm$ tracks is performed with a time of flight analysis as in the case of $\mathrm{K_S} \to \pi^\pm e^\mp \nu$, resulting in signal-to-background ratio of 75, a contamination level completely negligible in the following analysis.
The Δt-dependent efficiencies have been evaluated for each sample, $\varepsilon_{total}(\Delta t) = \varepsilon_{TEC} \times \varepsilon_{SEL}(\Delta t)$ where ε_{TEC}, about 99.5%, is the combination of Δt-independent efficiencies of trigger, machine background filter and event classification, and $\varepsilon_{SEL}(\Delta t)$ represents the efficiency of the analysis selections. Trigger efficiency is obtained from the rates of events with either one – EMC or DC based – or both triggers, while the efficiency of the machine background and the classification filters is estimated by pre-scaled minimum-bias samples. Event selection efficiencies are estimated by Monte Carlo simulations and corrected using independent data control samples of $\mathrm{K_S K_L} \to \pi^0\pi^0\ \ \pi^\pm e^\mp \nu$ and $\mathrm{K_S K_L} \to \pi^+\pi^-\ \ \pi^0\pi^0\pi^0$.

The number of identified events is shown in tab.1. The Δt distributions are summarized in fig.1 together with the efficiency $\varepsilon_{SEL}(\Delta t)$ in the range $0 < \Delta t < 320\ \tau_S$, with a bin width of 12 τ_S. The ratios in eqs.1 have been all obtained from these measurements, and the asymptotic values have been extracted by a fit in the region of $\Delta t \in (47, 275)\tau_S$ where the ratios are expected to be constant.

Systematics arising from the background evaluation and background subtraction, from the

Table 1: Numbers of events identified for each of the four event classes.

event sample	events
$\pi^+ e^- \nu \;\; \pi^0\pi^0\pi^0$	4750
$\pi^- e^+ \nu \;\; \pi^0\pi^0\pi^0$	4652
$\pi^+\pi^- \;\; \pi^+ e^- \nu$	15924863
$\pi^+\pi^- \;\; \pi^- e^+ \nu$	15708190

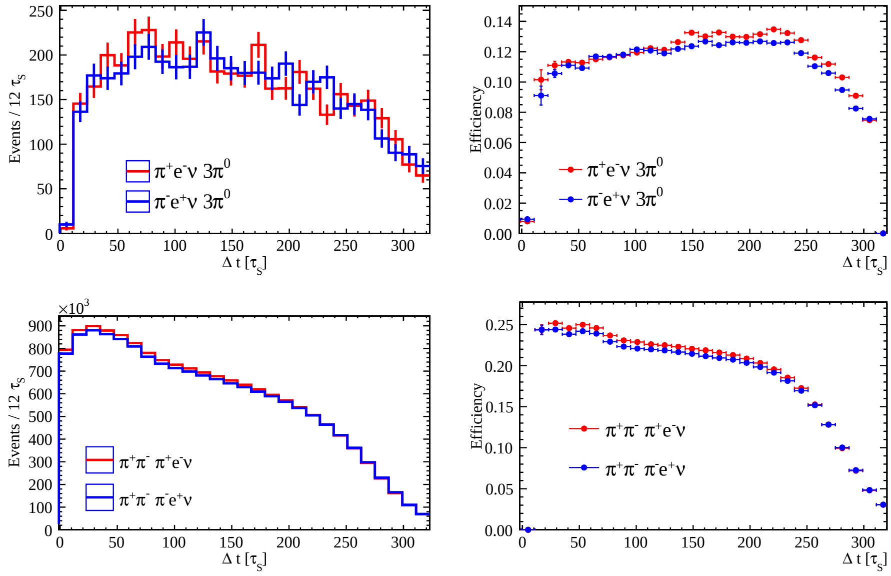

Figure 1: Left column: Rates as a function of Δt for the different channels. Right column: corresponding efficiencies, $\varepsilon_{SEL}(\Delta t)$.

selections cuts, and from bin-width choice, have been carefully evaluated [8], obtaining $0.9\ 10^{-3}$ for the CP-violation-sensitive ratio $R_{4,CP}$ and values from $1.4\ 10^{-2}$ to $1.9\ 10^{-2}$ for the other observables.

3. Results

We obtained all eight observables defined in eqs.(1)-(3)-(4):

$$
\begin{aligned}
R_{2,T} &= 0.991 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_N, \\
R_{4,T} &= 1.015 \pm 0.018_{stat} \pm 0.015_{syst} \pm 0.012_N, \\
R_{2,CPT} &= 1.004 \pm 0.017_{stat} \pm 0.014_{syst} \pm 0.012_N, \\
R_{4,CPT} &= 1.002 \pm 0.017_{stat} \pm 0.015_{syst} \pm 0.012_N, \\
R_{2,CP} &= 0.992 \pm 0.028_{stat} \pm 0.019_{syst}, \\
R_{4,CP} &= 1.00665 \pm 0.00093_{stat} \pm 0.00089_{syst}, \\
DR_{T,CP} &= 0.979 \pm 0.028_{stat} \pm 0.019_{syst}, \\
DR_{CPT} &= 1.005 \pm 0.029_{stat} \pm 0.019_{syst}
\end{aligned}
$$

where the third error is the uncertainty on the normalization factor $\mathcal{N} = \frac{BR(K_S \to \pi^+\pi^-)\cdot\Gamma_S}{BR(K_L \to \pi^0\pi^0\pi^0)\cdot\Gamma_L}$. A comparison of these results with the expected values, assuming CPT invariance, and T violation equal to the observed CP violation in mixing, is presented in Fig. 2. A total relative error of 2.5 %

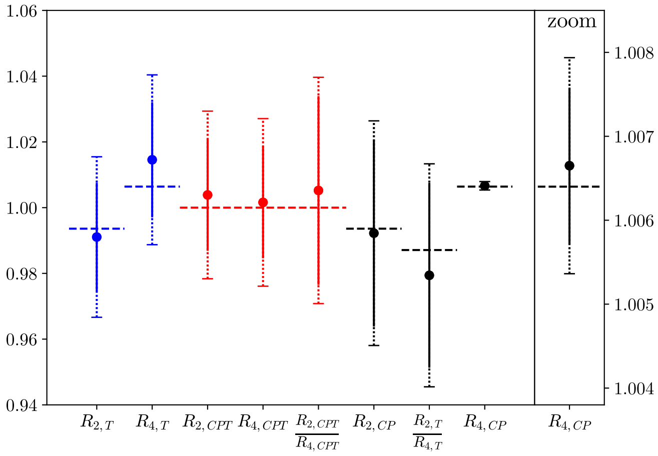

Figure 2: Comparison of the measured symmetry-violation-sensitive single and double ratios and their expected values (horizontal dashed lines) assuming CPT invariance, and T violation equal to the observed CP violation in mixing. Solid error bars are statistical uncertainties and dotted error bars represent total uncertainties, including error on the N factor for T and CPT-violation-sensitive ratios. The right-hand-side panel magnifies the region of the CP-violation-sensitive ratio $R_{4,CP}$.

is reached for the T and CPT-sensitive ratios, while error increases to 3.5 % for the double ratios (3) and (4). The measurement of $R_{4,\mathrm{CP}}$ benefits of the statistics of the dominant decay channels measured, leading to an error of 0.13 %.

No result on T and CPT observables shows evidence of symmetry violation. We observe CP violation in the ratio $R_{4,\mathrm{CP}}$ with a significance of 5.2σ, in agreement with the results of CP violation in $\mathrm{K}^0 - \overline{\mathrm{K}}^0$ mixing obtained with different observables from transitions $\mathrm{K}^0/\overline{\mathrm{K}}^0 \to K_{CP=+}$.

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