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A direct test of $\mathcal{T}$, $\mathcal{CP}$ and $\mathcal{CPT}$ symmetries in transitions of neutral kaons with KLOE data

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Abstract. Direct tests of $\mathcal{T}$, $\mathcal{CP}$, $\mathcal{CPT}$ symmetries in transitions processes of neutral kaons are briefly reviewed. The exchange of *in* and *out* states required for a genuine test involving time-reversal is implemented exploiting the entanglement of $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs produced at a ϕ-factory.

A data sample collected by the KLOE experiment at DAΦNE corresponding to an integrated luminosity of about 1.7 fb^{-1} is analysed to study the $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^- \pi e\nu$ and $\phi \to \mathrm{K_S K_L} \to \pi e\nu\, 3\pi^0$ processes, and to perform the first direct tests of $\mathcal{T}$ and $\mathcal{CPT}$ symmetries in kaon transitions with a precision of few percent, and to observe $\mathcal{CP}$ violation with this novel method.

1. Introduction

Testing the discrete symmetries of a physical system constitutes one of the most powerful tool to understand the underlying interactions and their theoretical description. The neutral kaon system at a ϕ-factory combines its peculiar flavour oscillations, charge-parity ($\mathcal{CP}$) and time-reversal ($\mathcal{T}$) violation, into an Einstein-Podolsky-Rosen (EPR) entangled system, revealing surprising features [1, 2, 3]. In order to realize direct tests of $\mathcal{T}$, $\mathcal{CP}$, $\mathcal{CPT}$ symmetries in neutral kaon transition processes, it is necessary to compare the probability of a reference transition with its symmetry conjugate. The exchange of *in* and *out* states required for a genuine test involving an anti-unitary transformation implied by time-reversal $\mathcal{T}$, can be implemented exploiting the entanglement of $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs [4, 5], as briefly described in the next section.

2. Direct test of discrete symmetries with neutral kaons

The initial kaon pair produced in $\phi \to \mathrm{K}^0\bar{\mathrm{K}}^0$ decays can be rewritten in terms of any pair of orthogonal states:

$$|i\rangle = \frac{1}{\sqrt{2}}\{|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle - |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle\} = \frac{1}{\sqrt{2}}\{|\mathrm{K}_+\rangle|\mathrm{K}_-\rangle - |\mathrm{K}_-\rangle|\mathrm{K}_+\rangle\} \,. \quad (1)$$

Here the states $|\mathrm{K}_-\rangle$, $|\mathrm{K}_+\rangle$ are defined as the states which cannot decay into pure $\mathcal{CP} = \pm 1$ final states, $\pi\pi$ or $3\pi^0$, respectively [4, 5]. The condition of orthogonality $\langle \mathrm{K}_-|\mathrm{K}_+\rangle = 0$, corresponds to assume negligible direct $\mathcal{CP}$ and/or $\mathcal{CPT}$ violation contributions in the decay, while the

$\Delta S = \Delta Q$ rule is also assumed, so that the two flavor orthogonal eigenstates $|\mathrm{K}^0\rangle$ and $|\bar{\mathrm{K}}^0\rangle$ are identified by the charge of the lepton in semileptonic decays.

Thus, exploiting the perfect anticorrelation of the states implied by Eq.(1), it is possible to have a "flavor-tag"or a "$\mathcal{CP}$-tag", i.e. to infer the flavor (K^0 or $\bar{\mathrm{K}}^0$) or the $\mathcal{CP}$ (K_+ or K_-) state of the still alive kaon by observing a specific flavor decay ($\pi^+\ell^-\nu$ or $\pi^-\ell^+\bar{\nu}$, in short ℓ^+ or ℓ^-) or $\mathcal{CP}$ decay ($\pi\pi$ or $3\pi^0$) of the other (and first decaying) kaon in the pair. Then the decay of the surviving kaon into a semileptonic (ℓ^+ or ℓ^-), $\pi\pi$ or $3\pi^0$ final state, filter the kaon final state as a flavor or $\mathcal{CP}$ state.

In this way one can identify a reference transition (e.g. $\mathrm{K}^0 \to \mathrm{K}_-$) and its symmetry conjugate (e.g. the $\mathcal{CPT}$-conjugated $\mathrm{K}_- \to \bar{\mathrm{K}}^0$), and directly compare them through the corresponding ratios of probabilities. The observable ratios for the various symmetry tests can be defined as follows [6, 7]:

$$R_{2,\mathcal{T}} \equiv \frac{I(\ell^-, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^+; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} = 1 - 4\Re\epsilon + 4\Re x_+ + 4\Re y \ , \quad (2)$$

$$R_{4,\mathcal{T}} \equiv \frac{I(\ell^+, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^-; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} = 1 + 4\Re\epsilon + 4\Re x_+ - 4\Re y \ , \quad (3)$$

$$R_{2,\mathcal{CP}} \equiv \frac{I(\ell^-, 3\pi^0; \Delta t \gg \tau_S)}{I(\ell^+, 3\pi^0; \Delta t \gg \tau_S)} = 1 - 4\Re\epsilon_S - 4\Re x_- + 4\Re y \ , \quad (4)$$

$$R_{4,\mathcal{CP}} \equiv \frac{I(\pi\pi, \ell^+; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^-; \Delta t \gg \tau_S)} = 1 + 4\Re\epsilon_L - 4\Re x_- - 4\Re y \ , \quad (5)$$

$$R_{2,\mathcal{CPT}} \equiv \frac{I(\ell^-, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^-; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} = 1 - 4\Re\delta + 4\Re x_+ - 4\Re x_- \ , \quad (6)$$

$$R_{4,\mathcal{CPT}} \equiv \frac{I(\ell^+, 3\pi^0; \Delta t \gg \tau_S)}{I(\pi\pi, \ell^+; \Delta t \gg \tau_S)} \cdot \frac{1}{D_{\mathcal{CPT}}} = 1 + 4\Re\delta + 4\Re x_+ + 4\Re x_- \ . \quad (7)$$

where $I(f_1, f_2; \Delta t \gg \tau_S)$ is the double decay rate into decay products f_1 and f_2 as a function of the difference of kaon decay times $\Delta t = t_2 - t_1$ in the asymptotic region $\Delta t \gg \tau_S$ [1, 4, 5], with f_1 occurring before f_2 decay and $\Delta t > 0$. The constant factor $D_{\mathcal{CPT}}$ is defined as:

$$D_{\mathcal{CPT}} = \frac{\left|\langle 3\pi^0|T|\mathrm{K}_-\rangle\right|^2}{\left|\langle \pi^+\pi^-|T|\mathrm{K}_+\rangle\right|^2} = \frac{\mathrm{BR}\left(\mathrm{K_L} \to 3\pi^0\right)}{\mathrm{BR}\left(\mathrm{K_S} \to \pi^+\pi^-\right)} \frac{\Gamma_L}{\Gamma_S} \ .$$

with the last r.h.s. equality valid with a high degree of accuracy, at least $\mathcal{O}(10^{-7})$. Therefore $D_{\mathcal{CPT}}$ can be determined from measurable branching fractions and lifetimes of $\mathrm{K_{S,L}}$ states [5, 6]. For $\Delta t = 0$ one has by construction no symmetry violation, within our assumptions. The measurement of any deviation from the prediction $R_{i,SS} = 1$ (with $SS = \mathcal{T}, \mathcal{CP}$, or $\mathcal{CPT}$, and $i = 2, 4$) imposed by the symmetry invariance is a direct signal of the symmetry violation built in the time evolution of the system. The following double ratios independent of the factor $D_{\mathcal{CPT}}$ can also be defined:

$$DR_{\mathcal{T},\mathcal{CP}} \equiv \frac{R_{2,\mathcal{T}}}{R_{4,\mathcal{T}}} \equiv \frac{R_{2,\mathcal{CP}}}{R_{4,\mathcal{CP}}} = 1 - 8\Re\epsilon + 8\Re y \ , \quad (8)$$

$$DR_{\mathcal{CPT}} \equiv \frac{R_{2,\mathcal{CPT}}}{R_{4,\mathcal{CPT}}} = 1 - 8\Re\delta - 8\Re x_- \ . \quad (9)$$

The r.h.s. of Eqs.(2)-(9) is evaluated to first order in small parameters; ϵ and δ are the usual $\mathcal{T}$ and $\mathcal{CPT}$ violation parameters in the neutral kaon mixing, respectively, and $\epsilon_{S,L} = \epsilon \pm \delta$ the $\mathcal{CP}$ impurities in the physical states $\mathrm{K_S}$ and $\mathrm{K_L}$; the small parameter y describes a possible

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$\mathcal{CPT}$ violation in the $\Delta S = \Delta Q$ semileptonic decay amplitudes, while x_+ and x_- describe $\Delta S \neq \Delta Q$ semileptonic decay amplitudes with $\mathcal{CPT}$ invariance and $\mathcal{CPT}$ violation, respectively. Therefore the r.h.s. of Eqs.(2)-(9) shows the effect of symmetry violations only in the the effective Hamiltonian description of the neutral kaon system according to the Weisskopf-Wigner approximation, without the presence of other possible sources of symmetry violations. The small spurious effects due to the release of our assumptions are also shown, including possible $\Delta S = \Delta Q$ rule violations ($x_+, x_- \neq 0$) and/or direct $\mathcal{CPT}$ violation effects ($y \neq 0$). It is worth noting that the direct $\mathcal{CP}$ ϵ' effects are fully negligible in the asymptotic region $\Delta t \gg \tau_S$ [4, 5].

3. Experimental results

The KLOE-2 collaboration recently completed the analysis of a data sample corresponding to an integrated luminosity $L = 1.7$ fb^{-1} collected at the DAΦNE ϕ-factory, and measured all eight observables defined in Eqs.(2)-(9). The Δt distributions of the $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^- \, \pi e \nu$ and $\phi \to \mathrm{K_S K_L} \to \pi e \nu \, 3\pi^0$ processes are studied in the asymptotic region $\Delta t \gg \tau_S$. A time of flight technique is used to identify semileptonic decays for both $\mathrm{K_S}$ and $\mathrm{K_L}$. $\mathrm{K_L} \to 3\pi^0$ decays are identified reconstructing the decay point and time using a trilateration method applied to the best candidate set of six reconstructed photons from π^0 decays. Residual background for the $\phi \to \mathrm{K_S K_L} \to \pi e \nu \, 3\pi^0$ channel is evaluated with the aid of Monte Carlo (MC) simulation and subtracted. Signal selection efficiencies are evaluated from MC and corrected with data using independent control samples. The Δt distributions of observables ratios (2)-(9) are then constructed and fitted with a constant. The case of $DR_{\mathcal{CPT}}$ is shown in Fig.1, as an example.

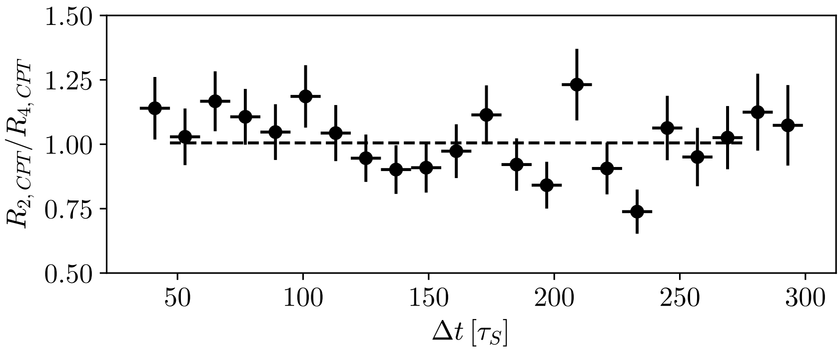

Figure 1. The measured Δt distribution in the asymptotic region for the double ratio $DR_{\mathcal{CPT}}$. The dashed line denotes the result of a fit with a constant.

The final results obtained for the eight observable ratios (2)-(9) are summarized in Fig.2, and compared with the expected values from $\mathcal{CPT}$ invariance and $\mathcal{T}$ violation extrapolated from observed $\mathcal{CP}$ violation in the $\mathrm{K}^0 - \bar{\mathrm{K}}^0$ mixing [8].

For the $\mathcal{T}$ and $\mathcal{CPT}$ single ratios a total error of 2.5 % is reached, while for the double ratios (8) and (9) the total error is increased to 3.5 %, with the advantage of in principle a doubled sensitivity to violation effects, and of independence from the $D_{\mathcal{CPT}}$ factor. The measurement of the single ratio $R_{4,\mathcal{CP}}$ benefits of highly allowed decay rates for the involved channels, reaching an error of 0.13 %.

The double ratio $DR_{\mathcal{CPT}}$ is our best observable for testing $\mathcal{CPT}$, free from approximations and model independent, while $DR_{\mathcal{T},\mathcal{CP}}$ assumes no direct $\mathcal{CPT}$ violation and is even under $\mathcal{CPT}$, therefore it does not disentangle $\mathcal{T}$ and $\mathcal{CP}$ violation effects, contrary to the genuine $\mathcal{T}$ and $\mathcal{CP}$ single ratios.

No result on $\mathcal{T}$ and $\mathcal{CPT}$ observables shows evidence of symmetry violation. We observe $\mathcal{CP}$ violation in transitions in the single ratio $R_{4,\mathcal{CP}}$ with a significance of 5.2σ, in agreement with

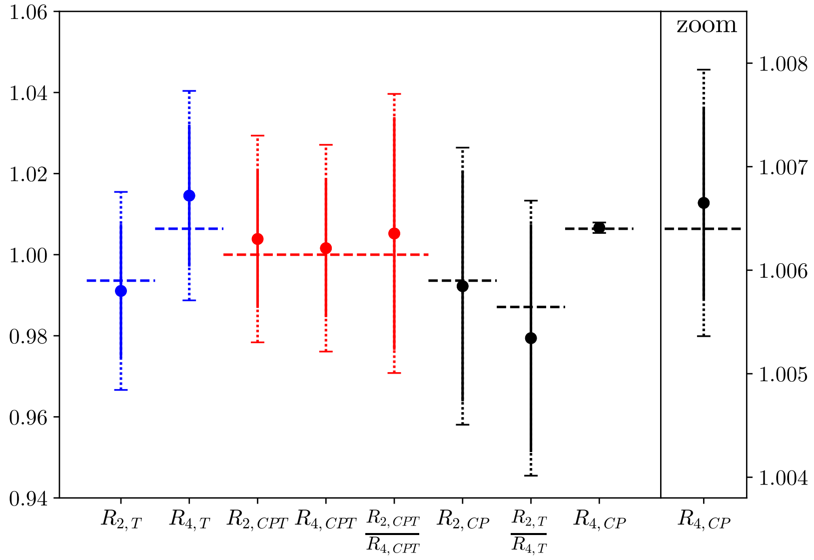

Figure 2. Comparison of the measured symmetry-violation-sensitive single and double ratios (2)-(9) and their expected values (horizontal dashed lines). Solid error bars denote statistical uncertainties and dotted error bars represent total uncertainties (including systematic uncertainties and the error on the $D_{\mathcal{CPT}}$ factor in case of single $\mathcal{T}$ and $\mathcal{CPT}$-violation sensitive ratios). The right-hand-side panel magnifies the region of the $\mathcal{CP}$-violation-sensitive ratio $R_{4,\mathcal{CP}}$.

the known $\mathcal{CP}$ violation in the $K^0 - \bar{K}^0$ mixing [8] using a different observable.

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