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TESTING DISCRETE SYMMETRIES IN TRANSITIONS WITH ENTANGLED NEUTRAL KAONS*

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A direct test of the T, CP and CPT symmetries in the neutral kaon system can be performed comparing a transition process $i \to f$ to its symmetry conjugated one. The exchange of *in* and *out* states required for genuine tests involving the time-reversal T can be performed exploiting the entanglement of the kaon pair produced at a ϕ-factory. In particular, using this method, it would be possible to perform a very clean and fully robust CPT test, which might shed light on possible new CPT-violating mechanisms. It is being implemented with the KLOE-2 experiment at the DAΦNE facility in Frascati, where a statistical sensitivity of $\mathcal{O}(10^{-3})$ on the newly proposed observable quantities could be reached.

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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. For instance, CP violation in the Standard Model (SM) arises from the single physically relevant phase in the three families Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix. The existence of this matrix conveys the fact that the quarks that participate in weak processes are a linear combination of mass eigenstates. This important mechanism has been validated in the past years with experiments probing the CP symmetry, especially in K and B meson decays.

A general approach to directly test discrete symmetries consists in comparing a transition $i \to f$ to its symmetry conjugated process. One advantage of this approach resides in the fact that in many physical phenomena,

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the perturbing effect does not appear at first order in perturbation theory. In fact, it would be sufficient that the perturbation breaks a symmetry of the non-perturbed states. This vanishing effect at first order for the diagonal elements, like *e.g.* the case of the electric dipole moment for T violation, is not present for transitions (non-diagonal elements) [1].

Transition processes for neutral mesons are experimentally accessible thanks to the maximal entanglement of the neutral meson pairs produced at meson factories. In this paper, possible T, CP and CPT tests in the neutral kaon system at a ϕ-factory are described [2, 3]. In particular, the proposed CPT test is very clean and fully robust, and might shed light on possible new CPT-violating mechanisms, or further improve the precision of the present experimental limits [3].

2. Direct test of discrete symmetries with neutral kaons

In order to implement a direct test of the T, CP and CPT symmetries, the Einstein–Podolsky–Rosen (EPR) entanglement of neutral kaons produced at a ϕ-factory is exploited. In fact, in this case, the initial state of the neutral kaon pair produced in $\phi \to K^0 \bar{K}^0$ decay can be rewritten in terms of any pair of orthogonal states $|K_+\rangle$ and $|K_-\rangle$

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

Let us consider the states $|K_+\rangle$, $|K_-\rangle$ defined as follows: $|K_+\rangle$ is the state filtered by the decay into $\pi\pi$ ($\pi^+\pi^-$ or $\pi^0\pi^0$), a pure CP $= +1$ state; analogously $|K_-\rangle$ is the state filtered by the decay into $3\pi^0$, a pure CP $= -1$ state. Their orthogonal states correspond to the states which cannot decay into $\pi\pi$ or $3\pi^0$, defined, respectively, as

$$\begin{aligned} \left|\widetilde{K}_-\right\rangle &\propto \left[|K_{\rm L}\rangle - \eta_{\pi\pi} \, |K_{\rm S}\rangle \right] , \\ \left|\widetilde{K}_+\right\rangle &\propto \left[|K_{\rm S}\rangle - \eta_{3\pi^0} \, |K_{\rm L}\rangle \right] , \end{aligned} \quad (2)$$

with $\eta_{\pi\pi} = \langle \pi\pi|T|K_{\rm L}\rangle / \langle \pi\pi|T|K_{\rm S}\rangle$ and $\eta_{3\pi^0} = \langle 3\pi^0|T|K_{\rm S}\rangle / \langle 3\pi^0|T|K_{\rm L}\rangle$. With these definitions of states, it can be shown that the condition of orthogonality $\langle K_-|K_+\rangle = 0$, (*i.e.* $|K_+\rangle \equiv |\widetilde{K}_+\rangle$ and $|K_-\rangle \equiv |\widetilde{K}_-\rangle$) corresponds to assume negligible direct CP (or CPT) violation contributions, assumption quite well satisfied for neutral kaons [3]. The validity of the $\Delta S = \Delta Q$ rule is also assumed, so that the two flavor orthogonal eigenstates $|K^0\rangle$ and $|\bar{K}^0\rangle$ are identified by the charge of the lepton in semileptonic decays, *i.e.* a $|K^0\rangle$ can decay into $\pi^-\ell^+\nu$ and not into $\pi^+\ell^-\bar{\nu}$, and *vice versa* for a $|\bar{K}^0\rangle$[1].

[1] It is important to underline that both these assumptions can be relaxed for some specific observables, as discussed below.

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

In this way, one can experimentally access — for instance — the transition $K^0 \to K_+$, taken as reference, and $K_+ \to K^0$, $\bar{K}^0 \to K_+$ and $K_+ \to \bar{K}^0$, *i.e.* the T, CP and CPT conjugated transitions, respectively. All possible transitions can be divided into four categories of events, corresponding to independent T, CP and CPT tests, as listed in Table I. One can

TABLE I

Scheme of possible reference transitions and their associated T-, CP- or CPT-conjugated processes accessible at a ϕ-factory.

Reference	T-conjug.	CP-conjug.	CPT-conjug.
$K^0 \to K_+$	$K_+ \to K^0$	$\bar{K}^0 \to K_+$	$K_+ \to \bar{K}^0$
$K^0 \to K_-$	$K_- \to K^0$	$\bar{K}^0 \to K_-$	$K_- \to \bar{K}^0$
$K_+ \to \bar{K}^0$	$\bar{K}^0 \to K_+$	$K_+ \to K^0$	$K^0 \to K_+$
$K_- \to \bar{K}^0$	$\bar{K}^0 \to K_-$	$K_- \to K^0$	$K^0 \to K_-$

directly compare the probabilities for the reference transition and the conjugated one defining the following ratios of probabilities for the T symmetry test:

$$
\begin{aligned}
R_{1,\mathrm{T}}(\Delta t) &= P\left[K_+(0) \to \bar{K}^0(\Delta t)\right]/P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] , \\
R_{2,\mathrm{T}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right]/P\left[K_-(0) \to K^0(\Delta t)\right] , \\
R_{3,\mathrm{T}}(\Delta t) &= P\left[K_+(0) \to K^0(\Delta t)\right]/P\left[K^0(0) \to K_+(\Delta t)\right] , \\
R_{4,\mathrm{T}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right]/P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] , \qquad (3)
\end{aligned}
$$

for the CP symmetry test:

$$
\begin{aligned}
R_{1,\mathrm{CP}}(\Delta t) &= P\left[K_+(0) \to \bar{K}^0(\Delta t)\right]/P\left[K_+(0) \to K^0(\Delta t)\right] , \\
R_{2,\mathrm{CP}}(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right]/P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] , \\
R_{3,\mathrm{CP}}(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right]/P\left[K^0(0) \to K_+(\Delta t)\right] , \\
R_{4,\mathrm{CP}}(\Delta t) &= P\left[K_-(0) \to K^0(\Delta t)\right]/P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] , \qquad (4)
\end{aligned}
$$

or for the CPT symmetry test:

$$\begin{aligned} R_{1,\mathrm{CPT}}(\Delta t) &= P\left[K_+(0)\to \bar{K}^0(\Delta t)\right]/P\left[K^0(0)\to K_+(\Delta t)\right] , \\ R_{2,\mathrm{CPT}}(\Delta t) &= P\left[K^0(0)\to K_-(\Delta t)\right]/P\left[K_-(0)\to \bar{K}^0(\Delta t)\right] , \\ R_{3,\mathrm{CPT}}(\Delta t) &= P\left[K_+(0)\to K^0(\Delta t)\right]/P\left[\bar{K}^0(0)\to K_+(\Delta t)\right] , \\ R_{4,\mathrm{CPT}}(\Delta t) &= P\left[\bar{K}^0(0)\to K_-(\Delta t)\right]/P\left[K_-(0)\to K^0(\Delta t)\right] . \end{aligned} \quad (5)$$

The measurement of any deviation from the prediction $R_{i,\mathrm{S}}(\Delta t) = 1$ imposed by the symmetry invariance (with $\mathrm{S} = \mathrm{T}, \mathrm{CP}$, or CPT) is a clean and direct signal of the symmetry violation.

It is worth noting that for $\Delta t = 0$

$$R_{1,\mathrm{S}}(0) = R_{2,\mathrm{S}}(0) = R_{3,\mathrm{S}}(0) = R_{4,\mathrm{S}}(0) = 1\,, \quad (6)$$

i.e. the S-violating effect is built in the time evolution of the system, and it is absent at $\Delta t = 0$, within our approximations.

For $\Delta t \gg \tau_{\mathrm{S}}$, assuming the presence of S violation only in the mass matrix[2] and nothing else, one gets

$$\begin{aligned} R_{2,\mathrm{T}}(\Delta t \gg \tau_{\mathrm{S}}) &\simeq 1 - 4\Re\epsilon\,, \\ R_{4,\mathrm{T}}(\Delta t \gg \tau_{\mathrm{S}}) &\simeq 1 + 4\Re\epsilon\,, \end{aligned} \quad (7)$$

$$\begin{aligned} R_{2,\mathrm{CP}}(\Delta t \gg \tau_{\mathrm{S}}) &\simeq 1 - 4\Re\epsilon_{\mathrm{S}}\,, \\ R_{4,\mathrm{CP}}(\Delta t \gg \tau_{\mathrm{S}}) &\simeq 1 + 4\Re\epsilon_{\mathrm{L}}\,, \end{aligned} \quad (8)$$

$$\begin{aligned} R_{2,\mathrm{CPT}}(\Delta t \gg \tau_{\mathrm{S}}) &\simeq 1 - 4\Re\delta\,, \\ R_{4,\mathrm{CPT}}(\Delta t \gg \tau_{\mathrm{S}}) &\simeq 1 + 4\Re\delta\,, \end{aligned} \quad (9)$$

i.e. the S-violating effect built in the time evolution reaches a "plateau" regime and dominates in this limit.

At a ϕ-factory, one can define two observable ratios for each symmetry test

$$R^{\mathrm{exp}}_{2,\mathrm{T}}(\Delta t) \equiv \frac{I\left(\ell^-, 3\pi^0; \Delta t\right)}{I(\pi\pi, \ell^+; \Delta t)}\,; \qquad R^{\mathrm{exp}}_{4,\mathrm{T}}(\Delta t) \equiv \frac{I\left(\ell^+, 3\pi^0; \Delta t\right)}{I(\pi\pi, \ell^-; \Delta t)}\,, \quad (10)$$

$$R^{\mathrm{exp}}_{2,\mathrm{CP}}(\Delta t) \equiv \frac{I\left(\ell^-, 3\pi^0; \Delta t\right)}{I\left(\ell^+, 3\pi^0; \Delta t\right)}\,; \qquad R^{\mathrm{exp}}_{4,\mathrm{CP}}(\Delta t) \equiv \frac{I(\pi\pi, \ell^+; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)}\,, \quad (11)$$

$$R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t) \equiv \frac{I\left(\ell^-, 3\pi^0; \Delta t\right)}{I(\pi\pi, \ell^-; \Delta t)}\,; \qquad R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t) \equiv \frac{I\left(\ell^+, 3\pi^0; \Delta t\right)}{I(\pi\pi, \ell^+; \Delta t)}\,, \quad (12)$$

[2] With $\epsilon_{\mathrm{S,L}} = \epsilon \pm \delta$, ϵ and δ, the usual T- and CPT-violation parameters in the neutral kaon mixing, respectively.

where $I(f_1, f_2; \Delta t)$ are the double decay rates into decay products f_1 and f_2 as a function of the difference of kaon decay times Δt [2, 4], with f_1 occurring before f_2 decay for $\Delta t > 0$, and *vice versa* for $\Delta t < 0$.

They are related to the $R_{i,\mathrm{S}}(\Delta t)$ ratios defined in Eqs. (3)–(5) as follows, for $\Delta t \geq 0$:

$$\begin{aligned} R^{\mathrm{exp}}_{2,\mathrm{S}}(\Delta t) &= R_{2,\mathrm{S}}(\Delta t) \times D_{\mathrm{S},2}\,, \\ R^{\mathrm{exp}}_{4,\mathrm{S}}(\Delta t) &= R_{4,\mathrm{S}}(\Delta t) \times D_{\mathrm{S},4}\,, \end{aligned} \tag{13}$$

whereas for $\Delta t < 0$, one has

$$\begin{aligned} R^{\mathrm{exp}}_{2,\mathrm{S}}(\Delta t) &= R_{1,\mathrm{S}}(|\Delta t|) \times D_{\mathrm{S},2}\,, \\ R^{\mathrm{exp}}_{4,\mathrm{S}}(\Delta t) &= R_{3,\mathrm{S}}(|\Delta t|) \times D_{\mathrm{S},4}\,, \end{aligned} \tag{14}$$

with the following relations among the constant terms:

$$\begin{aligned} D_{\mathrm{T},2} &= (1+4\Re y) \times D_{\mathrm{CPT}}\,; & D_{\mathrm{T},4} &= (1-4\Re y) \times D_{\mathrm{CPT}}\,, \\ D_{\mathrm{CP},2} &= (1+4\Re y)\,; & D_{\mathrm{CP},4} &= (1-4\Re y)\,, \\ D_{\mathrm{CPT},2} &= D_{\mathrm{CPT}}\,; & D_{\mathrm{CPT},4} &= D_{\mathrm{CPT}}\,, \end{aligned} \tag{15}$$

with the small parameter y describing a possible CPT violation in the $\Delta S = \Delta Q$ semileptonic decay amplitudes, and

$$D_{\mathrm{CPT}} = \frac{\left|\langle 3\pi^0|T|K_-\rangle\right|^2}{\left|\langle \pi\pi|T|K_+\rangle\right|^2} = \frac{\mathrm{BR}\left(K_{\mathrm{L}} \to 3\pi^0\right)}{\mathrm{BR}\left(K_{\mathrm{S}} \to \pi\pi\right)} \frac{\mathit{\Gamma}_{\mathrm{L}}}{\mathit{\Gamma}_{\mathrm{S}}}\,. \tag{16}$$

The last r.h.s. equality holds with a high degree of accuracy, at least $\mathcal{O}(10^{-7})$. The value of D_{CPT} can be therefore directly evaluated from branching ratios and lifetimes.

In case of the CPT test, particular attention must be paid to the presence of direct CP violation contributions in the decay amplitudes. Even though, in principle, it could mimic CPT violation effects, it turns out to be totally irrelevant for the plateau region $\Delta t \gg \tau_{\mathrm{S}}$ (see detailed description in Ref. [3]). The effect of a possible violation of the $\Delta S = \Delta Q$ rule is also not affecting the CPT test in the same region with the double ratio defined as

$$\frac{R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t \gg \tau_{\mathrm{S}})}{R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t \gg \tau_{\mathrm{S}})} = 1 - 8\Re\delta - 8\Re x_-\,, \tag{17}$$

with x_- describing CPT violation in the $\Delta S \neq \Delta Q$ semileptonic decay amplitudes. Therefore, the double ratio (17) constitutes one of the most robust observables for our proposed CPT test. It is independent of D_{CPT}, and in the limit $\Delta t \gg \tau_{\rm S}$, it exhibits a pure and genuine CPT violating effect, even without the assumptions of the validity of the $\Delta S = \Delta Q$ rule and of negligible contaminations from direct CP violation.

The KLOE-2 experiment at the DAΦNE facility [5] aims at reaching a total integrated luminosity $L \geq 5$ fb^{-1} and could make a precise measurement of all observable ratios $R^{\rm exp}_{i,{\rm S}}(\Delta t)$ [6]. By considering a large Δt interval in the statistically most populated region, *e.g.* $0 \leq \Delta t \leq 300\ \tau_{\rm S}$, a statistical sensitivity on the double ratio (17) of 3.0×10^{-3} can be obtained for $L = 5$ fb^{-1} [3]. Once translated into an uncertainty on $\Re\delta$, these results will improve its present limit.

3. Conclusions

A novel test of the T, CP and CPT symmetries has been studied in the neutral kaon system based on the direct comparison of a transition probability with its symmetry-reversed transition. The appropriate preparation and detection of *in* and *out* states in both the reference and the reverse processes is made by exploiting the EPR entanglement of neutral kaons produced in a ϕ-factory and using their decays as filtering measurements of the kaon states only.

In particular, the proposed CPT test is fully robust and might shed light on possible sources of CPT violation. Spurious effects induced by CP violation in the decay and/or a violation of the $\Delta S = \Delta Q$ rule have been shown to be either negligible or disentangled by the dependence with the time evolution.

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REFERENCES

[1] J. Bernabeu, F. Martinez-Vidal, *Rev. Mod. Phys.* **87**, 165 (2015).

[2] J. Bernabeu, A. Di Domenico, P. Villanueva-Perez, *Nucl. Phys. B* **868**, 102 (2013).

[3] J. Bernabeu, A. Di Domenico, P. Villanueva-Perez, *J. High Energy Phys.* **1510**, 139 (2015).

[4] A. Di Domenico (ed.), *Handbook on Neutral Kaon Interferometry at a ϕ-factory*, *Frascati Phys. Ser.* **43** (2007).

[5] G. Amelino-Camelia *et al.*, *Eur. Phys. J. C* **68**, 619 (2010).

[6] A. Gajos, *Acta Phys. Pol. B* **48**, 1975 (2017), this issue.