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Direct Test of T and CPT Symmetries with Entangled Neutral Mesons

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In this paper a method to perform direct T and CPT symmetry tests is briefly discussed, exploiting the Einstein–Podolsky–Rosen correlations of neutral kaon pairs produced at a ϕ -factory. The KLOE-2 experiment at DAΦNE, the Frascati ϕ -factory, could make statistically significant tests of this type.

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1. Introduction

In general any *theoretical* connection among the parameters describing T, CP or CPT violation, as given by the CPT theorem, does not imply a corresponding connection among the *experimental* results of the T, CP or CPT tests.

In this paper the possibility to perform a direct test of time-reversal T symmetry in the neutral kaon system is discussed. It requires the exchange of *in* and *out* states of a transition process. The only existing result [1] for neutral kaons showing a non-zero asymmetry comparing the rates of a reference process ($K^0 \rightarrow \bar{K}^0$) and its T conjugated one ($\bar{K}^0 \rightarrow K^0$) cannot be considered a direct test, because the T and CP conjugated processes are identical in this case, and cannot be distinguished[†]. In fact here *direct test* means a test whose outcome is independent of the result of any other discrete symmetry test, as discussed in detail in Refs. [3–7].

In order to implement such a direct test of the T symmetry, and also of the CPT symmetry which requires as well the inversion of *in* and *out* states, it has been suggested to exploit the Einstein–Podolsky–Rosen (EPR) entanglement of neutral mesons produced at a ϕ -factory (or B-factory) [4–7]. In fact in this case the initial state of the neutral kaon pair produced in $\phi \rightarrow K^0 \bar{K}^0$ decay can be rewritten in terms of any pair of orthogonal states $|K_+\rangle$ and $|K_-\rangle$:

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

Here one can 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:

$$|\tilde{K}_-\rangle \propto [|K_L\rangle - \eta_{\pi\pi}|K_S\rangle],$$

$$|\tilde{K}_+\rangle \propto [|K_S\rangle - \eta_{3\pi^0}|K_L\rangle], \quad (2)$$

with $\eta_{\pi\pi} = \langle\pi\pi|T|K_L\rangle/\langle\pi\pi|T|K_S\rangle$ and $\eta_{3\pi^0} = \langle 3\pi^0|T|K_S\rangle/\langle 3\pi^0|T|K_L\rangle$. With these definitions of states, it can be shown that the condition of orthogonality $\langle K_-|K_+\rangle = 0$ (i.e. $|K_+\rangle \equiv |\tilde{K}_+\rangle$ and $|K_-\rangle \equiv |\tilde{K}_-\rangle$) corresponds to assume negligible direct CP (or CPT) violation contributions (i.e. $\epsilon', \epsilon'_{00} \ll \epsilon$), assumption quite well satisfied for neutral kaons (see detailed discussion in Appendix A of Ref. [7]). 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 $|\bar{K}^0\rangle$.

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 the transitions listed in Table, which can be divided into four categories of events, corresponding to independent T, CP and CPT tests.

TABLE

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.
$K^0 \rightarrow K_+$	$K_+ \rightarrow K^0$	$\bar{K}^0 \rightarrow K_+$	$K_+ \rightarrow \bar{K}^0$
$K^0 \rightarrow K_-$	$K_- \rightarrow K^0$	$\bar{K}^0 \rightarrow K_-$	$K_- \rightarrow \bar{K}^0$
$\bar{K}^0 \rightarrow K_+$	$K_+ \rightarrow \bar{K}^0$	$K^0 \rightarrow K_+$	$K_+ \rightarrow K^0$
$\bar{K}^0 \rightarrow K_-$	$K_- \rightarrow \bar{K}^0$	$K^0 \rightarrow K_-$	$K_- \rightarrow K^0$

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[†]It is worth mentioning that in the neutral B meson system, such a direct T test has been recently accomplished [2], exploiting a similar methodology as discussed in the following.

2. T and CPT symmetry test

For the direct T symmetry test one can define the following ratios of probabilities:

$$R_1(\Delta t) = P[K^0(0) \rightarrow K_+(\Delta t)] / P[K_+(0) \rightarrow K^0(\Delta t)],$$

$$R_2(\Delta t) = P[K^0(0) \rightarrow K_-(\Delta t)] / P[K_-(0) \rightarrow K^0(\Delta t)],$$

$$R_3(\Delta t) = P[\bar{K}^0(0) \rightarrow K_+(\Delta t)] / P[K_+(0) \rightarrow \bar{K}^0(\Delta t)],$$

$$R_4(\Delta t) = P[\bar{K}^0(0) \rightarrow K_-(\Delta t)] / P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]. \quad (3)$$

The measurement of any deviation from the prediction $R_i(\Delta t) = 1$ imposed by T invariance is a signal of T violation.

At a ϕ -factory the corresponding observable quantities are two ratios, $R_2^{\text{exp}}(\Delta t)$ and $R_4^{\text{exp}}(\Delta t)$ of double decay rates $I(f_1, f_2; \Delta t)$ into decay products f_1 and f_2 as a function of the difference of kaon decay times Δt [7, 8], with f_1 occurring before f_2 decay for $\Delta t > 0$, and vice versa for $\Delta t < 0$. For $\Delta t > 0$ one has

$$R_2^{\text{exp}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} = R_2(\Delta t) \times D, \quad (4)$$

$$R_4^{\text{exp}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_4(\Delta t) \times D, \quad (5)$$

while for $\Delta t < 0$:

$$R_2^{\text{exp}}(\Delta t) = \frac{D}{R_3(|\Delta t|)}, \quad (6)$$

$$R_4^{\text{exp}}(\Delta t) = \frac{D}{R_1(|\Delta t|)}. \quad (7)$$

Here the normalization constant D , assuming no CPT violation in semileptonic decays, is $D = \{\text{BR}(K_L \rightarrow 3\pi^0) \Gamma_L\} / \{\text{BR}(K_S \rightarrow \pi\pi) \Gamma_S\}$.

For the direct CPT symmetry test one can define the following ratios of probabilities, similarly as for the T test:

$$R_{1,\text{CPT}}(\Delta t) =$$

$$P[K^0(0) \rightarrow K_+(\Delta t)] / P[K_+(0) \rightarrow \bar{K}^0(\Delta t)],$$

$$R_{2,\text{CPT}}(\Delta t) =$$

$$P[K^0(0) \rightarrow K_-(\Delta t)] / P[K_-(0) \rightarrow \bar{K}^0(\Delta t)],$$

$$R_{3,\text{CPT}}(\Delta t) =$$

$$P[\bar{K}^0(0) \rightarrow K_+(\Delta t)] / P[K_+(0) \rightarrow K^0(\Delta t)],$$

$$R_{4,\text{CPT}}(\Delta t) =$$

$$P[\bar{K}^0(0) \rightarrow K_-(\Delta t)] / P[K_-(0) \rightarrow K^0(\Delta t)]. \quad (8)$$

The measurement of any deviation from the prediction $R_{i,\text{CPT}}(\Delta t) = 1$ imposed by CPT invariance is a signal of CPT violation.

At a ϕ -factory the corresponding observable quantities are, for $\Delta t > 0$:

$$R_{2,\text{CPT}}^{\text{exp}}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_{2,\text{CPT}}(\Delta t) \times D_{\text{CPT}}, \quad (9)$$

$$R_{4,\text{CPT}}^{\text{exp}}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} = R_{4,\text{CPT}}(\Delta t) \times D_{\text{CPT}}, \quad (10)$$

while for $\Delta t < 0$:

$$R_{2,\text{CPT}}^{\text{exp}}(\Delta t) = \frac{D_{\text{CPT}}}{R_{1,\text{CPT}}(|\Delta t|)}, \quad (11)$$

$$R_{4,\text{CPT}}^{\text{exp}}(\Delta t) = \frac{D_{\text{CPT}}}{R_{3,\text{CPT}}(|\Delta t|)}. \quad (12)$$

Here the normalization constant D_{CPT} is $D_{\text{CPT}} = \{\text{BR}(K_L \rightarrow 3\pi^0) \Gamma_L\} / \{\text{BR}(K_S \rightarrow \pi\pi) \Gamma_S\}$ without any assumption on CPT violation in semileptonic decays.

The KLOE-2 experiment at DAΦNE with an integrated luminosity of $\mathcal{O}(10 \text{ fb}^{-1})$ [9] could make statistically significant T and CPT tests, measuring the ratios $R_2^{\text{exp}}(\Delta t)$, $R_4^{\text{exp}}(\Delta t)$, $R_{2,\text{CPT}}^{\text{exp}}(\Delta t)$ and $R_{4,\text{CPT}}^{\text{exp}}(\Delta t)$ integrated in the statistically most populated Δt region, $0 \leq \Delta t \leq 300 \tau_S$ [7]. In this region these ratios are expected to be constant and a precise knowledge of the normalization constants D and D_{CPT} is needed in order to not weaken the significance of the test. A precise reconstruction of $K_S \rightarrow \pi\ell\nu$ and $K_L \rightarrow 3\pi^0$ decays is needed, and specific studies are in progress at KLOE-2 [10, 11].

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