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Testing fundamental physical principles with entangled neutral K mesons

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Abstract. The neutral kaon doublet is one of the most intriguing systems in nature. Entangled pairs of neutral K mesons produced in ϕ-meson decays offer a unique possibility to perform important tests of fundamental discrete symmetries as well as of basic principles of quantum mechanics.
This paper will focus on a novel method to perform direct T and CPT symmetry tests exploiting the Einstein-Podolsky-Rosen correlations of neutral kaon pairs produced at a ϕ-factory. The statistical significance of the test achievable with the KLOE-2 experiment at DAΦNE, the Frascati ϕ-factory, is also briefly discussed.

1 Introduction

Entanglement and its consequences - in particular the violation of Bell inequalities, which defies our concepts of realism and locality [1] - have been proven to play a key role in Nature by many experiments for various quantum systems. A recent formulation of the Bell's inequality for entangled neutral kaons produced at a ϕ-factory [2] (overcoming some serious drawbacks in the past formulations) makes this inequality experimentally testable also for the $K^0-\bar{K}^0$ system. It's worth mentioning that - surprisingly - CP violation in this case turns out to be a key ingredient to make the inequality violated by Quantum Mechanics. This subject has been thoroughly discussed by B. Hiesmayr in her contribution [3].

CPT invariance is ensured by the CPT theorem in the context of any local quantum field theory with Lorentz invariance and Hermiticity, as in the Standard Model. It has been confirmed by all present experimental tests, particularly in the neutral kaon system where strong limits have been set to a variety of possible CPT violation effects which might arose in a quantum gravity framework [4–6]. The latest results on this subject obtained by the KLOE experiment at DAΦNE, the Frascati ϕ-factory, and prospects for the KLOE-2 experiment [7] have been presented by C. Bloise in her contribution [8].

Among the several fundamental physical principles which might be tested in the neutral kaon system [9], this paper focuses on a novel method to perform a direct test of the T (time-reversal) symmetry, directly inverting the *in* and *out* states of the transition process by exploiting the Einstein-Podolsky-Rosen correlations of neutral kaon pairs produced at a ϕ-factory to realize this inversion.
In fact in case of a transition process, due to the antiunitarity of the operator implementing the symmetry transformation, T invariance requires that the rate for the reaction $i \to f$ equals that of the reaction

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$f_T \rightarrow i_T$, with *in* and *out* states exchanged and T-*inverted* (for spinless particles this corresponds to the reaction $f \rightarrow i$).

In the past years there was only one measurement showing a violation of T invariance, consisting in a non-zero value of the Kabir asymmetry [10], comparing the rates of the process $K^0 \rightarrow \bar{K}^0$ and its T conjugated one $\bar{K}^0 \rightarrow K^0$ [11]. However, this process has the feature that $K^0 \rightarrow \bar{K}^0$ is a CPT even transition, so that T and CP transformations are identical in this case, and the corresponding observables are not independent. Therefore it is impossible to separate T violation from CP violation in the Kabir asymmetry. This is not a desirable situation in a *direct* test, where the *direct* evidence of the violation should be clearly showed independently from the results of CP violation and without any connection with them[1].

Another subtle drawback related to the Kabir asymmetry is the one discussed in Ref. [12], where it is pointed out that the T-violation contribution in the Kabir asymmetry is constant in time and directly proportional to $\Delta\Gamma$, the width difference of the $K_{S,L}$ mass eigenstates. This signals the presence of non-negligible initial state interaction effects which in principle might weaken the test, and it would be desirable to avoid them in a direct genuine test. Moreover in the $B^0 - \bar{B}^0$ system no asymmetry is expected to be found, since in this case $\Delta\Gamma$ almost vanishes (within the SM).

In order to overcome these difficulties it has been suggested to exploit the Einstein-Podolsky-Rosen (EPR) [13] entanglement of neutral mesons produced at a ϕ-factory (or B-factory) [14–16]. In fact in this case other transitions than $K^0 \rightarrow \bar{K}^0$ or $\bar{K}^0 \rightarrow K^0$ can be observed, independently from CP or CPT test results, thus implementing a *genuine* direct test of the T symmetry. A *direct* CPT test, requiring as well the inversion of *in* and *out* states, might be also implemented with the same methodology.

2 Direct T and CPT symmetry tests at a ϕ-factory

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 $|K_-\rangle$:

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

Here one can consider the states $|K_+\rangle$, $|K_-\rangle$ defined, respectively, as the states filtered by the decay into $\pi\pi$ ($\pi^+\pi^+$ or $\pi^0\pi^0$), a pure CP = +1 state, and by the decay into $3\pi^0$, a pure CP = −1 state.

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 $3\pi^0$) of the other (and first decaying) kaon in the pair.

In this way one can experimentally access other transitions than $K^0 \rightarrow \bar{K}^0$ or $\bar{K}^0 \rightarrow K^0$. These new accessible processes can be divided into four categories of events, as summarized in Table 1.

For instance, one can consider $K^0 \rightarrow K_+$ as the reference process, where the initial state K^0 is identified at time t_1 with the flavor tag, and the final state K_+ is identified at a subsequent time $t_2 \geq t_1$ with a CP decay.

I) The T transformed process is $K_+ \rightarrow K^0$; any asymmetry in the rate between $K^0 \rightarrow K_+$ and $K_+ \rightarrow K^0$ would be a genuine T violating effect.

[1] Obviously the theoretical connection between CP and T symmetries given by the CPT theorem does not imply an experimental identity between them.

Table 1. Reference transitions and their associated T, CP or CPT conjugated processes.

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

II) The CP transformed process is $\bar{K}^0 \to K_+$; any asymmetry in the rate between $K^0 \to K_+$ and $\bar{K}^0 \to K_+$ would be a genuine CP violating effect.

III) The CPT transformed process is $K_+ \to \bar{K}^0$; any asymmetry in the rate between $K^0 \to K_+$and $K_+ \to \bar{K}^0$ would be a genuine CPT violating effect.

One may check that the events used for the asymmetries in I), II), and III) are completely independent from each other. Moreover, T violating effects would depend on $\Delta t = t_2 - t_1$ and would be present even in the limit $\Delta\Gamma \to 0$.

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

$$\begin{aligned} R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right]/P\left[K_+(0) \to K^0(\Delta t)\right] \\ R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right]/P\left[K_-(0) \to K^0(\Delta t)\right] \\ R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right]/P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\ R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right]/P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] . \end{aligned} \tag{2}$$

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 observable quantity is the differential decay rate $I(f_1, f_2; \Delta t)$ of the state $|i\rangle$ to decay into decay products f_1 and f_2 at a proper time difference $\Delta t = t_2 - t_1$ [9]. As a consequence the experimentally observable quantities corresponding to the four ratios $R_i(\Delta t)$ are two ratios of decay intensities $R_2^{\rm exp}(\Delta t)$ and $R_4^{\rm exp}(\Delta t)$ defined and connected to the ratios $R_i(\Delta t)$ as follows. For $\Delta t > 0$ one has:

$$R_2^{\rm exp}(\Delta t) \equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} = R_2(\Delta t) \times D \ , \ \ R_4^{\rm exp}(\Delta t) \equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_4(\Delta t) \times D \tag{3}$$

while for $\Delta t < 0$:

$$R_2^{\rm exp}(\Delta t) = \frac{D}{R_3(|\Delta t|)} \ , \ \ R_4^{\rm exp}(\Delta t) = \frac{D}{R_1(|\Delta t|)} \ . \tag{4}$$

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

The KLOE-2 experiment at DAΦNE with an integrated luminosity of $O(10\ {\rm fb}^{-1})$ [7] could make a statistically significant T test, measuring the ratios $R_2^{\rm exp}(\Delta t)$ and $R_4^{\rm exp}(\Delta t)$ integrated in the statistically most populated Δt region, $0 \leq \Delta t \leq 300\ \tau_S$, as discussed in detail in Ref. [16].

It must be mentioned that recently, based on this methodology, the first direct observation of T violation has been accomplished in the neutral B meson system [17].

Similarly to the proposed T test, one can define the following ratios of probabilities for a CPT test:

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

The measurement of any deviation from the prediction $R_{i,\mathrm{CPT}}(\Delta t) = 1$ imposed by CPT invariance is a signal of CPT violation. At a ϕ-factory the corresponding observable quantities are, for $\Delta t > 0$:

$$\begin{aligned}
R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t) &\equiv \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)} = R_{2,\mathrm{CPT}}(\Delta t) \times D_{\mathrm{CPT}} \\
R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t) &\equiv \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)} = R_{4,\mathrm{CPT}}(\Delta t) \times D_{\mathrm{CPT}}
\end{aligned} \quad (6)$$

while for $\Delta t < 0$:

$$R^{\mathrm{exp}}_{2,\mathrm{CPT}}(\Delta t) = \frac{D_{\mathrm{CPT}}}{R_{1,\mathrm{CPT}}(|\Delta t|)} \quad , \quad R^{\mathrm{exp}}_{4,\mathrm{CPT}}(\Delta t) = \frac{D_{\mathrm{CPT}}}{R_{3,\mathrm{CPT}}(|\Delta t|)} \; . \quad (7)$$

Here the normalization constant D_{CPT} is defined as the D constant in the T test, but without requiring any assumption on CPT violation in semileptonic decays.

The direct CPT test would be theoretically very clean and the KLOE-2 experiment could make a statistically significant test [16].

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