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A direct test of time-reversal symmetry in the neutral K meson system with $K_S \to \pi\ell\nu$ and $K_L \to 3\pi^0$ at KLOE-2

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Abstract. Quantum entanglement of K and B mesons allows for a direct experimental test of time-reversal symmetry independent of $\mathcal{CP}$ violation. The $\mathcal{T}$ symmetry can be probed by exchange of initial and final states in the reversible transitions between flavor and CP-definite states of the mesons which are only connected by the $\mathcal{T}$ conjugation. While such a test was successfully performed by the BaBar experiment with neutral B mesons, the KLOE-2 detector can probe $\mathcal{T}$-violation in the neutral kaons system by investigating the process with $K_S \to \pi^{\pm} l^{\mp} \nu_l$ and $K_L \to 3\pi^0$ decays. Analysis of the latter is facilitated by a novel reconstruction method for the vertex of $K_L \to 3\pi^0$ decay which only involves neutral particles. Details of this new vertex reconstruction technique are presented as well as prospects for conducting the direct $\mathcal{T}$ symmetry test at the KLOE-2 experiment.

1 Introduction

Among possible experimental ways to study the $\mathcal{T}$ symmetry violation, it is of special interest to test the symmetry directly, i.e. by comparing amplitudes for a process and its time inverse. For spin 0 particles such as neutral mesons the inverse process is obtained simply by the exchange of initial and final states. To date, the only evidence of $\mathcal{T}$ violation in the neutral kaon system was found by the CPLEAR experiment through measurement of the Kabir asymmetry [1]. However, use of the $\mathcal{CPT}$-even $K^0 \leftrightarrows \bar{K}^0$ process raised some controversy due to possible influence of $\mathcal{CP}$ violation on the result. Quantum entanglement of neutral kaons produced at the ϕ factory allows to obtain and compare kaon transitions between flavour-definite and $\mathcal{CP}$-definite states and their time inverses which are only connected by time reversal conjugation [2]. This allows for a direct test of the $\mathcal{T}$ symmetry independent of $\mathcal{CP}$ and $\mathcal{CPT}$. A similar idea was recently used by the BaBar experiment to directly observe $\mathcal{T}$ violation in the neutral B meson system [3, 4]. In turn, KLOE-2 is capable of performing the first direct $\mathcal{T}$ symmetry test with neutral kaons.

2 Principle of the test

For a direct $\mathcal{T}$ symmetry test with neutral kaons, a set of transitions must be chosen such that their $\mathcal{T}$-inverses can be observed as well and their *in* and *out* states may be unambiguously identified by

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observation of kaon decay final states. These conditions are met by states with definite strangeness $\{K^0, \bar{K}^0\}$ and $\mathcal{CP}$-eigenstates $\{K_+, K_-\}$. The former are identified by semileptonic decays $K^0 \to \pi^- \ell^+ \nu_l$ and $\bar{K}^0 \to \pi^+ \ell^- \bar{\nu}_l$ (with assumption of the $\Delta Q = \Delta S$ rule) whereas the latter must decay hadronically into two pions ($\pi^+\pi^-$, $\pi^0\pi^0$) for $\mathcal{CP}$=+1 or $3\pi^0$ for $\mathcal{CP}$=-1. These two bases are connected by four possible transitions, listed in Table 1. Independence of the measured asymmetry of $\mathcal{CP}$-violating effects is guaranteed by the fact that for any transition its time inverse is not identical with its $\mathcal{CP}$-conjugate, by contrast with e.g. the Kabir asymmetry in $K^0 \leftrightarrows \bar{K}^0$. Probability of each transition

Table 1. Transitions between flavour-definite and CP-definite states of neutral kaons and their time-reversal conjugates. Each of the transitions is experimentally identified by a time-ordered pair of kaon decays.

	Transition	Identified by	$\mathcal{T}$-conjugate	Identified by
1	$K^0 \to K_+$	$(\ell^-, \pi\pi)$	$K_+ \to K^0$	$(3\pi^0, \ell^+)$
2	$K^0 \to K_-$	$(\ell^-, 3\pi^0)$	$K_- \to K^0$	$(\pi\pi, \ell^+)$
3	$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(3\pi^0, \ell^-)$
4	$\bar{K}^0 \to K_-$	$(\ell^+, 3\pi^0)$	$K_- \to \bar{K}^0$	$(\pi\pi, \ell^-)$

can be compared with its time-reversal conjugate in search of a discrepancy which would signal $\mathcal{T}$-violation. Experimentally, final states of kaons in the transitions would be identified directly by recording their decays while recognition of a living kaon state is uniquely possible at KLOE-2 as kaons produced in the ϕ meson decay exhibit quantum entanglement which guarantees the living kaon to be in an orthogonal state to its first-decaying partner. This way the double decay rates can be collected as a function of proper decay time difference for the two kaons decaying through chosen channels and the following ratios can be defined as observables of the $\mathcal{T}$ symmetry test:

$$R_1^{exp}(\Delta t) = \mathrm{I}(\ell^-, \pi\pi; \Delta t) \;/\; \mathrm{I}(3\pi^0, \ell^+; \Delta t), \tag{1}$$

$$R_2^{exp}(\Delta t) = \mathrm{I}(\ell^-, 3\pi^0; \Delta t) \;/\; \mathrm{I}(\pi\pi, \ell^+; \Delta t), \tag{2}$$

$$R_3^{exp}(\Delta t) = \mathrm{I}(\ell^+, \pi\pi; \Delta t) \;/\; \mathrm{I}(3\pi^0, \ell^-; \Delta t), \tag{3}$$

$$R_4^{exp}(\Delta t) = \mathrm{I}(\ell^+, 3\pi^0; \Delta t) \;/\; \mathrm{I}(\pi\pi, \ell^-; \Delta t). \tag{4}$$

Among the above ratios, R_2^{exp} and R_4^{exp} concern processes for which statistics sufficient for a significant test is expected by KLOE-2 [2]. These experimental observables are related to ratios of amplitudes by the following proportionality [5]:

$$R_2(\Delta t) = P[K^0(0) \to K_-(\Delta t)] \;/\; P[K_-(0) \to K^0(\Delta t)] = R_2^{exp}(\Delta t)/C, \tag{5}$$

$$R_4(\Delta t) = P[\bar{K}^0(0) \to K_-(\Delta t)] \;/\; P[K_-(0) \to \bar{K}^0(\Delta t)] = R_4^{exp}(\Delta t)/C, \tag{6}$$

where the constant $C = \frac{\mathrm{BR}(K_L \to 3\pi^0)\cdot\Gamma_L}{\mathrm{BR}(K_S \to \pi\pi)\cdot\Gamma_S}$ involves kaon parameters well determined i.a. by the KLOE experiment.

After extraction of the R_2 and R_4 probability ratios from (2) and (4), their asymptotic behaviour for $\Delta t \gg \tau_S$ can be compared with the theoretical expectation:

$$R_2(\Delta t \gg \tau_s) \simeq 1 - 4\Re\epsilon, \qquad R_4(\Delta t \gg \tau_s) \simeq 1 + 4\Re\epsilon, \tag{7}$$

in order to measure the $\mathcal{T}$-violating parameter $\Re\epsilon$ [2].

3 Reconstruction of events for the test at KLOE

The KLOE detector is located at the DAΦNE e^+e^- collider, a ϕ-factory operating at $\sqrt{s} \approx 1020$ MeV. In the years 1999–2006 KLOE has collected 2.5 fb^{-1} of data. KLOE is a barrel-shaped detector whose basic components are large drift chamber (DC) and electromagnetic calorimeter (EMC) immersed in magnetic field of 0.52 T. Recently the detector was upgraded to KLOE-2 [6] with addition of new calorimeters at small angles around the beam pipe [7] and a new Cylindrical-GEM inner tracker [8]. Processes required for the $\mathcal{T}$ test include semileptonic decays of neutral kaons with the partner kaon decaying into 2 or 3 pions. While for the 2-pion final state $\pi^+\pi^-$ can be chosen and well reconstructed from DC tracks, the $K_L \rightarrow 3\pi^0$ decay requires special treatment as it only includes neutral particles and the $K_S \rightarrow \pi\ell\nu$ decay does not provide full kinematic information on the event due to a missing neutrino. Therefore a special reconstruction method for $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay was prepared which uses only information on γ hits in the EMC. The decay point and time are reconstructed using a technique similar to GPS positioning. More details can be found in Ref. [9].

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