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 $CP$ 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 $K_S \to \pi^{\pm}\ell^{\mp}\nu$ 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 $CPT$-even $K^0 \leftrightarrow \bar{K}^0$ process raised some controversy due to possible influence of $CP$ violation on the result. Quantum entanglement of neutral kaons produced at the $\phi$ factory allows to obtain and compare kaon transitions between flavour-definite and $CP$-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 $CP$ and $CPT$. 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 \( CP \)-eigenstates \( \{K_+, K_-\} \). The former are identified by semileptonic decays \( K^0 \rightarrow \pi^- \ell^+ \nu_l \) and \( \bar{K}^0 \rightarrow \pi^+ \ell^- \bar{\nu}_l \) (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 \( CP=+1 \) or \( 3\pi^0 \) for \( CP=-1 \). These two bases are connected by four possible transitions, listed in Table 1. Independence of the measured asymmetry of \( CP \)-violating effects is guaranteed by the fact that for any transition its time inverse is not identical with its \( CP \)-conjugate, by contrast with e.g. the Kabir asymmetry in \( K^0 \rightarrow \bar{K}^0 \). Probability of each transition can be compared with its time-reversal conjugate in search of a discrepancy which would signal \( T \)-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 \( \phi \) 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 compared with its time-reversal conjugate in search of a discrepancy which would signal \( T \)-violation.

**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.

<table>
<thead>
<tr>
<th>Transition Identified by</th>
<th>( T )-conjugate Identified by</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^0 \rightarrow K_+ ) (( \ell^-, \pi\pi ); ( \Delta t ))</td>
<td>( K_+ \rightarrow K^0 ) (( 3\pi^0, \ell^+ ))</td>
</tr>
<tr>
<td>( K^0 \rightarrow K_- ) (( \ell^-, 3\pi^0 ))</td>
<td>( K_- \rightarrow K^0 ) (( \pi\pi, \ell^+ ))</td>
</tr>
<tr>
<td>( \bar{K}^0 \rightarrow K_+ ) (( \ell^+, \pi\pi ))</td>
<td>( K_+ \rightarrow \bar{K}^0 ) (( 3\pi^0, \ell^- ))</td>
</tr>
<tr>
<td>( \bar{K}^0 \rightarrow K_- ) (( \ell^+, 3\pi^0 ))</td>
<td>( K_- \rightarrow \bar{K}^0 ) (( \pi\pi, \ell^- ))</td>
</tr>
</tbody>
</table>

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]:

\[
R_2(\Delta t) = P[K^0(0) \rightarrow K_-(\Delta t)] / P[K_-(0) \rightarrow K^0(\Delta t)] = R_2^{exp}(\Delta t)/C, \\
R_4(\Delta t) = P[\bar{K}^0(0) \rightarrow K_-(\Delta t)] / P[K_-(0) \rightarrow \bar{K}^0(\Delta t)] = R_4^{exp}(\Delta t)/C,
\]

where the constant \( C = \frac{BR(K_+ \rightarrow 3\pi^0\Gamma_l)}{BR(K_+ \rightarrow \pi\pi \Gamma_l)} \) 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:

\[
R_2(\Delta t \gg \tau_S) \approx 1 - 4\Re \epsilon, \quad R_4(\Delta t \gg \tau_S) \approx 1 + 4\Re \epsilon,
\]

in order to measure the \( T \)-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 \( \phi \)-factory operating at \( \sqrt{s} \approx 1020 \text{ MeV} \). 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 $T$ 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 $K_L \to 3\pi^0$ decay requires special treatment as it only includes neutral particles and the $K_S \to \pi\ell\nu$ decay does not provide full kinematic information on the event due to a missing neutrino. Therefore a special reconstruction method for $K_L \to 3\pi^0 \to 6\gamma$ decay was prepared which uses only information on $\gamma$ 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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