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A direct test of $\mathcal{T}$ symmetry in the neutral K meson system with $\mathrm{K_S} \to \pi\ell\nu$ and $\mathrm{K_L} \to 3\pi^0$ 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

A direct test of the time-reversal symmetry in a single experiment is of great interest among possible ways to probe the $\mathcal{T}$ symmetry violation [1]. For particles with spin 0 such as pseudo-scalar mesons, a direct test may be obtained by observation of an asymmetry between a reaction from state i to state f and a reversed reaction $f \to i$. While the CPLEAR experiment measured a nonzero value of the Kabir asymmetry in neutral kaon oscillations [2], a controversy was raised as to whether this result was independent of $\mathcal{CP}$ violation as the $\mathrm{K}^0 \to \bar{\mathrm{K}^0}$ and $\bar{\mathrm{K}^0} \to \mathrm{K}^0$ transitions are connected by both the $\mathcal{T}$ and $\mathcal{CP}$ symmetries. Therefore, an idea was proposed to exploit the quantum correlations of neutral B and K meson pairs to observe reversible transitions between flavour and $\mathcal{CP}$-definite states of the mesons [3, 4]. Such a $\mathcal{T}$ symmetry test was successfully performed by the BaBar experiment with the entangled neutral B meson system [5]. In turn, the KLOE-2 detector at the DAΦNE ϕ-factory is capable of performing a statistically significant direct observation of $\mathcal{T}$ symmetry violation with neutral kaons independently of $\mathcal{CP}$ violation [4].

2 Transitions between flavour and $\mathcal{CP}$-definite neutral kaon states

Neutral kaon states may be described in a number of bases including flavour-definite states:

$$\mathcal{S}\,|\mathrm{K}^0\rangle = +1\,|\mathrm{K}^0\rangle\,, \qquad \mathcal{S}\,|\bar{\mathrm{K}^0}\rangle = -1\,|\bar{\mathrm{K}^0}\rangle\,, \tag{1}$$

as well as the states with definite $\mathcal{CP}$ parity:

$$|\mathrm{K}_+\rangle \;\; = \tfrac{1}{\sqrt{2}}\left[|\mathrm{K}^0\rangle + |\bar{\mathrm{K}^0}\rangle\right] \qquad \mathcal{CP} = +1, \tag{2}$$

$$|\mathrm{K}_-\rangle \;\; = \tfrac{1}{\sqrt{2}}\left[|\mathrm{K}^0\rangle - |\bar{\mathrm{K}^0}\rangle\right] \qquad \mathcal{CP} = -1. \tag{3}$$

State of the kaon can be identified at the moment of decay through observation of the decay final state. With the assumption of $\Delta S = \Delta Q$ rule[1], semileptonic kaon decays with positively and negatively charged leptons (later denoted as ℓ^+, ℓ^-) unambiguously identify the decaying state as K^0 and $\bar{\mathrm{K}^0}$ respectively. Similarly, the $\mathcal{CP}$-definite states K_+ and K_- are implied by decays to hadronic

[1] Althought an assumption, the $\Delta S = \Delta Q$ rule is well tested in semileptonic kaon decays [6]

final states with respectively two and three pions (denoted $\pi\pi$, 3π). In order to observe a transition between the $\{\mathrm{K}^0, \bar{\mathrm{K}^0}\}$ and $\{\mathrm{K}_+, \mathrm{K}_-\}$ states, both the *in* and *out* states must be identified in the respective basis. This is uniquely possible in the entangled system of neutral K mesons produced at a ϕ-factory. Due to conservation of $\phi(1^{--})$ quantum numbers, the $\phi \to \mathrm{K}^0\bar{\mathrm{K}^0}$ decay yields an anti-symmetric non-strange final state of the form:

$$|\phi\rangle \to \frac{1}{\sqrt{2}}\left(\left|\mathrm{K}^0(+\vec{p})\right\rangle\left|\bar{\mathrm{K}^0}(-\vec{p})\right\rangle - \left|\bar{\mathrm{K}^0}(+\vec{p})\right\rangle\left|\mathrm{K}^0(-\vec{p})\right\rangle\right), \tag{4}$$

which exhibits quantum entanglement between the two kaons in the EPR sense [7]. Thus, at the moment of decay of first of the K mesons (and, consequently, identification of its state) state of the partner kaon is immediately known to be orthogonal. This property allows for identification of state of the still-living kaon only by observing the decay of its partner. Its state can be then measured at the moment of decay after time Δt, possibly leading to observation of a transition between strangeness and CP-definite states. A list of all possible transitions is presented in Table 1. It is immediately visible that time-reversal conjugates of these transitions are not identical with neither their CP- nor CPT-conjugates which is crucial for independence of the test.

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

Table 1: Possible transitions between flavour and CP-definite states and their time-reversal conjugates. For each transition a time-ordered pair of decay products which identifies the respective states is given.

3 Observables of the test

For each of the transitions from Table 1 occurring in time Δt and its time-reversal conjugate a time-dependent ratio of probabilities can be defined as an observable of the $\mathcal{T}$ symmetry test. In the region where high statistics is expected at KLOE-2, however, two of them are important for the test:

$$R_2(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]} \sim \frac{\mathrm{I}(\ell^-, 3\pi^0; \Delta t)}{\mathrm{I}(\pi\pi, \ell^+; \Delta t)}, \tag{5}$$

$$R_4(\Delta t) = \frac{P[\bar{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \bar{\mathrm{K}}^0(\Delta t)]} \sim \frac{\mathrm{I}(\ell^+, 3\pi^0; \Delta t)}{\mathrm{I}(\pi\pi, \ell^-; \Delta t)}. \tag{6}$$

These quantities can be measured experimentally through numbers of events with certain pairs of decays occurring in time difference Δt. A deviation of these ratios from 1 would be an indication of $\mathcal{T}$ symmetry violation. Bernabeu *et al.* have simulated the behaviour of these ratios expected at KLOE-2 for $10 fb^{-1}$ of data [4] (Figure 1). At KLOE-2 the asymptotic region of R_2 and R_4 can be observed where their theoretical behaviour may be expressed as:

$$R_2(\Delta t) \overset{\Delta t \gg \tau_s}{\longrightarrow} 1 - 4\Re\epsilon, \tag{7}$$

$$R_4(\Delta t) \overset{\Delta t \gg \tau_s}{\longrightarrow} 1 + 4\Re\epsilon, \tag{8}$$

where $\epsilon = (\epsilon_S + \epsilon_L)/2$ is a T-violating parameter [4].

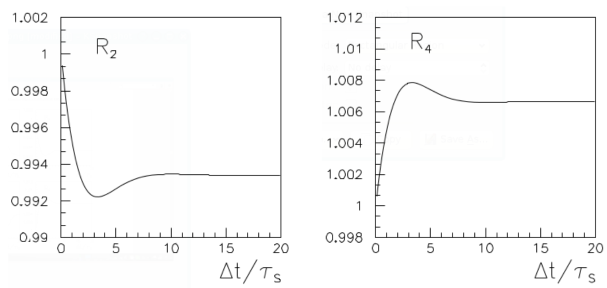

Figure 1: Simulated behavior of the probability ratios expected for $10 fb^{-1}$ of KLOE-2 data. The figure was adapted from [4].

4 Reconstruction of events for the test

The $\mathcal{T}$ symmetry test requires reconstruction of the processes with $\mathrm{K_S} \to \pi\pi$, $\mathrm{K_L} \to \pi^\pm \ell^\mp \nu$ and $\mathrm{K_S} \to \pi^\pm \ell^\mp \nu$, $\mathrm{K_L} \to 3\pi^0$ pairs of decays. While for $\mathrm{K_S} \to \pi\pi$ the $\pi^+\pi^-$ final state can be chosen to take advantage of good vertex and momentum reconstruction from charged pion tracks in the KLOE drift chamber, the $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ decay reconstruction is a challenging task.

This process only involves neutral particles resulting in the calorimeter clusters from six γ hits being the only recorded information. Moreover, this decay has to be reconstructed in cases where the partner $\mathrm{K_S}$ decays semileptonically and the missing neutrino prevents the use of kinematic constraints to aid $\mathrm{K_L} \to 3\pi^0$ reconstruction. Therefore, this process requires independent reconstruction.

5 The $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ decay vertex reconstruction

The aim of the new reconstruction method is to obtain the spatial coordinates and time of the $\mathrm{K_L}$ decay point by only using information on electromagnetic calorimeter clusters created by γ hits from $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$. Information available for i-th cluster includes its spatial location and recording time (X_i, Y_i, Z_i, T_i). The problem of localizing the vertex is then in its principle similar to GPS positioning and can be solved in a similar manner.

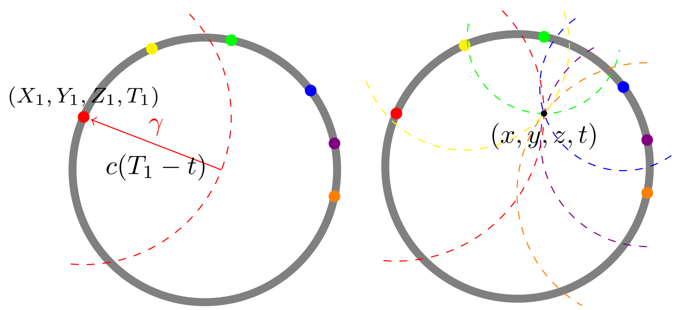

Figure 2: A scheme of $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ vertex reconstruction in the section view of KLOE-2 calorimeter barrel (grey circle). Colored dots denote clusters from γ hits. Left: a set of possible origin points of a γ which created a cluster is a sphere centered at the cluster (red dashed line) with radius parametrized by kaon flight time t. Right: intersection point of such spheres for all γ hits is the $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ decay point.

For each cluster a set of possible origin points of the incident γ is a sphere centered at the cluster with radius parametrized by an unknown γ origin time t (Figure 2, left). Then, definition of such sets for all available clusters yields a system of up to six equations:

$$(T_i - t)^2 c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2 \quad i = 1, \ldots, 6, \tag{9}$$

with the unknowns x,y,z and t. It is then easily noticed that the $K_L \to 3\pi^0 \to 6\gamma$ vertex is a common origin point of all photons which lies on an intersection of the spheres found as a solution of the above system (Figure 2, right). At least 4 clusters are required to obtain an analytic solution although additional two may be exploited to obtain a more accurate vertex numerically.

It is worth noting that this vertex reconstruction method directly yields kaon decay time in addition to spatial location which is useful for time-dependent interferometric studies such as the $\mathcal{T}$ symmetry test.

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