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STUDY OF THE $K_{\rm S}K_{\rm L} \to \pi\ell\nu 3\pi^0$ PROCESS FOR TIME REVERSAL SYMMETRY TEST AT KLOE-2*

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This work presents prospects for conducting a novel direct test of time-reversal symmetry at the KLOE-2 experiment. Quantum entanglement of neutral K meson pairs uniquely available at KLOE-2 allows to probe directly the time-reversal symmetry ($\mathcal{T}$) independently of $\mathcal{CP}$ violation. This is achieved by a comparison of probabilities for a transition between flavour and $\mathcal{CP}$-definite states and its inverse obtained through exchange of initial and final states. As such, a test requires the reconstruction of the $K_{\rm L} \to 3\pi^0$ decay accompanied by $K_{\rm S} \to \pi^{\pm}\ell^{\mp}\nu$ with good timing information, a new reconstruction method for this process is also presented which is capable of reconstructing the $K_{\rm L} \to 3\pi^0$ decay with decay time resolution of $\mathcal{O}(1\tau_{\rm S})$.

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1. Introduction

Well known for $\mathcal{CP}$-violating phenomena, neutral kaons may also be used to study directly the time-reversal symmetry although special care is necessary to prepare a $\mathcal{T}$ symmetry test which should be independent of $\mathcal{CP}$-violation effects. Such a test is possible with entangled neutral kaon pairs uniquely available at the DAΦNE ϕ-factory [1]. Kaon transitions between flavour-definite and $\mathcal{CP}$-definite states constitute processes for whom an exchange of initial and final state only corresponds to the time-reversal operation and not $\mathcal{CP}$ nor $\mathcal{CPT}$ conjugation. This allows for a direct test by comparison of amplitudes for a transition and its inverse independently of $\mathcal{CP}$ and $\mathcal{CPT}$. A similar principle was recently used by the BaBar experiment to observe $\mathcal{T}$-violation in the neutral B-meson system [2, 3]. In turn, KLOE-2 is capable of investigating time-reversal violation with neutral kaons.

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2. The direct $\mathcal{T}$ symmetry test

The entangled states of a pair of neutral K mesons produced in the ϕ-meson decay may be expressed in any suitable basis of orthogonal states such as flavour-definite states $\{K^0, \bar{K}^0\}$ or $\mathcal{CP}$-definite states $\{K_+, K_-\}$

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

Kaons can be identified in these bases through final state observation at the moment of their decay. If the $\Delta S = \Delta Q$ rule is assumed[1], the semileptonic decays with a positively and negatively charged leptons (later denoted as ℓ^+, ℓ^-) unambiguously tag the decaying state as K^0 and $\bar{K}^0$. Meanwhile, hadronic decay modes with two and three pions $(3\pi^0)$[2] are only possible for $\mathcal{CP}$ eigenstates K_+ (CP $= 1$) and K_- (CP $= -1$), respectively. Observation of a transition between $\mathcal{CP}$ and flavour-definite states also requires identification of kaon state at a point before its decay. This is uniquely possible with entangled neutral kaon pairs, as recognition of the state of the first decaying kaon guarantees its still-living partner to be in the orthogonal state at the moment of the first decay. Therefore, it is possible to obtain the transitions listed in Table I along with their time inverses. It is worth stressing that these transitions are connected with their $\mathcal{T}$-inverses only by time-reversal conjugation and not by $\mathcal{CP}$ nor $\mathcal{CPT}$ transformations. For each of the transitions from Table I, a measurement of the ratio of time-dependent probabilities of a transition and its inverse constitutes a test of $\mathcal{T}$ symmetry. At KLOE-2 [5], statistically significant tests are expected for transitions 2 and 4. The theoretical ratios R_2 and R_4 can be experimentally obtained from measurable ratios of double decay rates to which they are

TABLE I

Transitions between flavour and $\mathcal{CP}$-definite states of neutral kaons. For each transition, a time-ordered pair of final states indicating the decays of respective states is provided in parentheses.

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

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[1] The $\Delta S = \Delta Q$ rule is well tested in semileptonic kaon decays [4].

[2] Only $3\pi^0$ is a pure CP $= -1$ state.

proportional up to a constant:

$$R_2(\Delta t) = \frac{P\left[K^0(0) \to K_-(\Delta t)\right]}{P\left[K_-(0) \to K^0(\Delta t)\right]} \sim \frac{I\left(\ell^-, 3\pi^0; \Delta t\right)}{I\left(\pi\pi, \ell^+; \Delta t\right)}, \tag{2}$$

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

where Δt is the difference of proper decay times of the two kaons. Any discrepancy of the R_2 and R_4 ratios from unity would be a direct signal of $\mathcal{T}$ symmetry violation. At KLOE-2, the asymptotic behaviour of these ratios can be measured (see Fig. 1) in order to extract the $\mathcal{T}$-violating $\mathrm{Re}(\epsilon)$ parameter as the theoretical prediction for large time differences is $R_2(\Delta t) \xrightarrow{\Delta t \gg \tau_S} 1 - 4\,\mathrm{Re}(\epsilon)$ and $R_4(\Delta t) \xrightarrow{\Delta t \gg \tau_S} 1 + 4\,\mathrm{Re}(\epsilon)$.

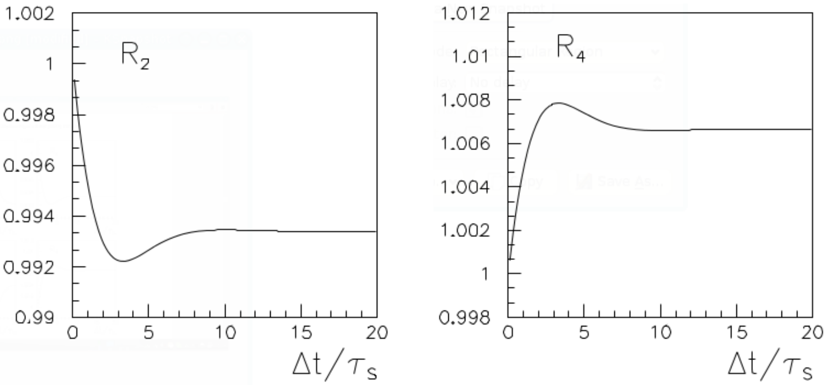

Fig. 1. Expected behaviour of the transition probability ratios R_2 and R_4 as a function of proper decay times difference Δt as simulated for 10 fb^{-1} of KLOE-2 data. Figure adapted from [1].

3. Experimental realization at KLOE-2 and DAΦNE

The DAΦNE ϕ-factory is an electron–positron collider operating at the energy of the ϕ resonance peak ($\sqrt{s} \approx 1020$ MeV) and predominantly producing ϕ mesons with small momentum ($\beta_\phi \approx 0.015$) whose decays provide pairs of charged or neutral kaons with branching fractions of about 49% and 34%, respectively. Kaon decays are recorded by the KLOE detector consisting of a cylindrical drift chamber (DC) surrounded by a sampling electromagnetic calorimeter (EMC). In the recent upgrade to KLOE-2, the region close to interaction point was filled with a novel cylindrical triple-GEM inner tracker (IT) to improve vertexing [6].

As shown in the previous section, a direct test of $\mathcal{T}$ symmetry at KLOE-2 requires ability to reconstruct two types of events: $K_{\mathrm{S}}K_{\mathrm{L}} \to \ell^{\pm}\pi^{\mp}\nu\, 3\pi^0$ and $K_{\mathrm{S}}K_{\mathrm{L}} \to \pi\pi\ \ell^{\pm}\pi^{\mp}\nu$. For construction of time-dependent decay distributions, kaon proper decay times should be determined with resolution of the order of 1 τ_{S}. In the case of $\pi^+\pi^-$ (chosen as the $\pi\pi$ state) and semileptonic final states, charged particle tracks provide good vertexing (and thus timing) information. The $K_{\mathrm{L}} \to 3\pi^0 \to 6\gamma$ decay, however, is a challenging reconstruction task as only neutral particles are involved and the only recorded information on this process are the γ hits in the EMC. For this decay, a new reconstruction method was prepared for KLOE-2.

4. $K_{\mathrm{L}} \to 3\pi^0$ decay reconstruction

The new reconstruction procedure uses only information on up to 6γ hits in the KLOE-2 EMC in order to reconstruct both spatial location and time of the $K_{\mathrm{L}} \to 3\pi^0 \to 6\gamma$ decay. For each of the photons, EMC provides information on the hit point and time (Fig. 2, left). Therefore, a set of possible origin points of the incident γ is a sphere centered at the EMC hit position with a radius dependent on the time of the K_{L} decay t. Such spheres for each available EMC γ hit constitute a system of equations

$$(T_i - t)^2c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2\,, \qquad i = 1, \ldots, 6\,. \tag{4}$$

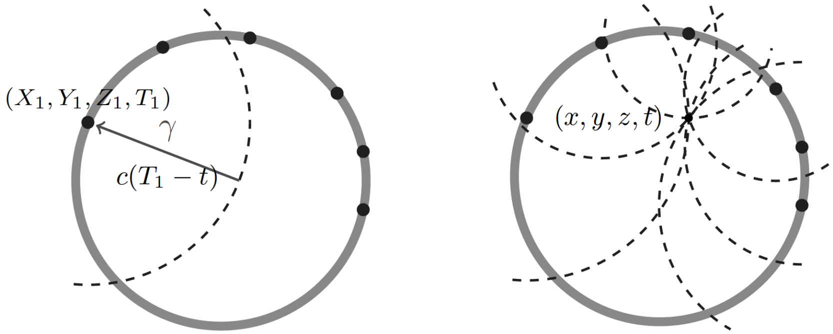

Fig. 2. Scheme of the $K_{\mathrm{L}} \to 3\pi^0 \to 6\gamma$ decay vertex reconstruction in cross section view of the KLOE EMC (grey ring).

As the $K_{\rm L}$ decay vertex is the common origin of all photons, it can be found as an intersection of all spheres defined above by solving the system of equations for x, y, z and t (Fig. 2, right). Although only 4 γ hits are necessary to solve the system, recording all 6 photons allows to improve the decay vertex resolution by numerical best satisfaction of the overdetermined system.

Performance of reconstruction was tested on a sample of MC-generated $K_{\rm L} \to 3\pi^0$ events. Resolution of proper $K_{\rm L}$ decay time was estimated for several regions of the decay vertex distance from the interaction point. Figure 3 shows the resulting resolution which is at the level of $\sim 2\ \tau_{\rm S}$ and remains constant with increasing $K_{\rm L}$ travelled path lengths in the whole range available in the detector. This temporal resolution is sufficient for the future $\mathcal{T}$ symmetry test at KLOE-2.

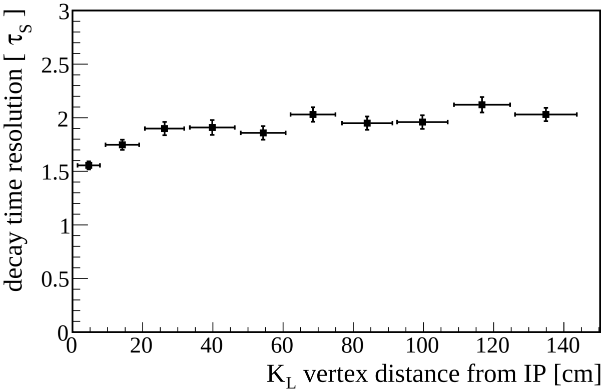

Fig. 3. Resolution of proper $K_{\rm L}$ decay time reconstructed for $K_{\rm L} \to 3\pi^0$ with the new method as a function of the decay vertex distance from the ϕ-decay point (IP).

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