Vol. 46 (2015) *ACTA PHYSICA POLONICA B* No 1

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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(Received October 24, 2014)

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 $\mathcal{O}(1\tau_{\rm S})$.

DOI:10.5506/APhysPolB.46.13
PACS numbers: 14.40.Df, 24.80.+y

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.

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 $\{K_+, K_-\}$

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

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	$K^0 \rightarrow K_+$	$(\ell^-, \pi\pi)$	$K_+ \rightarrow K^0$	$(3\pi^0, \ell^+)$
2	$K^0 \rightarrow K_-$	$(\ell^-, 3\pi^0)$	$K_- \rightarrow K^0$	$(\pi\pi, \ell^+)$
3	$\bar{K}^0 \rightarrow K_+$	$(\ell^+, \pi\pi)$	$K_+ \rightarrow \bar{K}^0$	$(3\pi^0, \ell^-)$
4	$\bar{K}^0 \rightarrow K_-$	$(\ell^+, 3\pi^0)$	$K_- \rightarrow \bar{K}^0$	$(\pi\pi, \ell^-)$

[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 $R_4(\Delta t) \xrightarrow{\Delta t \gg \tau_S} 1 + 4\,\mathrm{Re}(\epsilon)$.

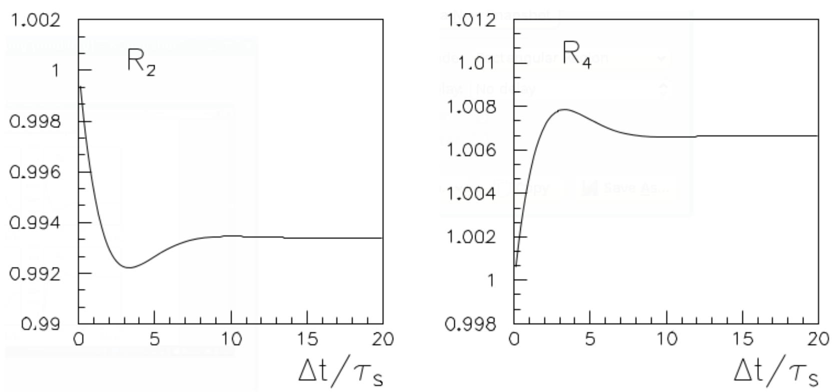

Fig. 1. Expected behaviour of the transition probability ratios R_2 and R_4 as a function of proper decay times difference Δt as simulated for 10 fb^{-1} of KLOE-2 data. Figure adapted from [1].

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: $K_S K_L \to \ell^{\pm}\pi^{\mp}\nu\, 3\pi^0$ and $K_S K_L \to \pi\pi\ \ell^{\pm}\pi^{\mp}\nu$. 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 $K_L \to 3\pi^0 \to 6\gamma$ 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. $K_L \to 3\pi^0$ 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 $K_L \to 3\pi^0 \to 6\gamma$ 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

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

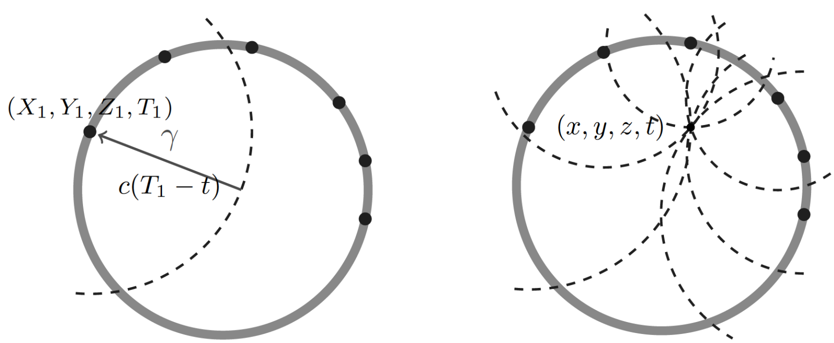

Fig. 2. Scheme of the $K_L \to 3\pi^0 \to 6\gamma$ decay vertex reconstruction in cross section view of the KLOE EMC (grey ring).

As the K_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 $K_\mathrm{L} \to 3\pi^0$ events. Resolution of proper K_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 $\sim 2\ \tau_\mathrm{S}$ and remains constant with increasing K_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.

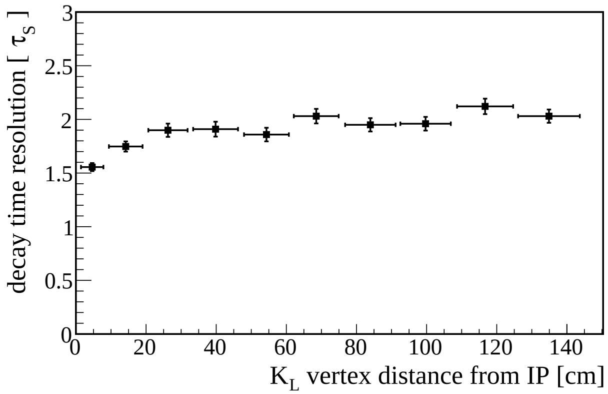

Fig. 3. Resolution of proper K_L decay time reconstructed for $K_\mathrm{L} \to 3\pi^0$ with the new method as a function of the decay vertex distance from the ϕ-decay point (IP).

This work was supported in part by the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3-CT-2004-506078; by the European Commission under the 7$^{\mathrm{th}}$ Framework Programme through the *Research Infrastructures* action of the *Capacities* Programme, Call: FP7-INFRASTRUCTURES-2008-1, Grant Agreement No. 227431; by the Polish National Science Centre through the Grants No. 0469/B/H03/2009/37, 0309/B/H03/2011/40, 2011/03/N/ST2/02641, 2011/01/D/ST2/00748, 2011/03/N/ST2/02652, 2013/08/M/ST2/00323 and by the Foundation for Polish Science through the MPD programme and the project HOMING PLUS BIS/2011-4/3.

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