# Study of the  $K_S K_L \rightarrow \pi \ell \nu 3 \pi^0$  process for time reversal symmetry test at KLOE-2

Aleksander Gajos on behalf of the KLOE-2 collaboration

The Marian Smoluchowski Institute of Physics, Jagiellonian University, Lojasiewicza 11, 30-348, Kraków, Poland aleksander.gajos@uj.edu.pl

This work presents prospects for conducting a novel direct test of timereversal 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  $K_L \to 3\pi^0$  decay accompanied by  $K_S \to \pi^{\pm} \ell^{\mp} \nu$  with good timing information, a new reconstruction method for this process is also presented which is capable of reconstructing the  $K_L \rightarrow 3\pi^0$  decay with decay time resolution of  $\mathcal{O}(1\tau_S)$ .

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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  $\phi$ -factory [\[1\]](#page-4-0). 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 [\[2,](#page-4-1) [3\]](#page-4-2). 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  $\phi$ 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  $\{\bar{K}_+, \bar{K}_-\}$ :

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

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<sup>[1](#page-1-0)</sup>, the semileptonic decays with a positively and negatively charged leptons (later denoted as  $(\ell^+, \ell^-)$  unambiguously tag the decaying state as  $\tilde{K}^0$  and  $\tilde{K}^0$ . Meanwhile, hadronic decay modes with two and three pions  $(3\pi^0)^2$  $(3\pi^0)^2$  are only possible for  $\mathcal{CP}$  eigenstates K<sub>+</sub> (CP=1) and K<sub>-</sub> (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 [1](#page-1-2) along with their time inverses. It is worth stressing that these transitions are connected with their  $\mathcal{T}$ -inverses only by timereversal conjugation and not by  $\mathcal{CP}$  nor  $\mathcal{CPT}$  transformations. For each of

Transition		$\tau$ -conjugate	
$K^0 \rightarrow K_+$	$(\ell^-,\pi\pi)$	$K_{+}\rightarrow K^{0}$	$(3\pi^0, \ell^+)$
$K^0 \rightarrow K_-$	$(\ell^-, 3\pi^0)$	$K_{-} \rightarrow K^{0}$	$(\pi\pi,\ell^+)$
$K^0 \rightarrow K_+$	$(\ell^+, \pi\pi)$	$K_{+}\rightarrow K^{0}$	$(3\pi^0, \ell^-)$
	$(\ell^+, 3\pi^0)$	$K^- \rightarrow K^0$	$(\pi\pi,\ell^-)$

<span id="page-1-2"></span>Table 1. Transitions between flavour and 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.

the transitions from table [1](#page-1-2) 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 [\[5\]](#page-4-3) 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 proportional

<span id="page-1-0"></span><sup>&</sup>lt;sup>1</sup> The  $\Delta S = \Delta Q$  rule is well tested in semileptonic kaon decays<sup>[\[4\]](#page-4-4)</sup>

<span id="page-1-1"></span><sup>&</sup>lt;sup>2</sup> Only  $3\pi^0$  is a pure CP=-1 state.

up to a constant:

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

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

where  $\Delta t$  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\)](#page-2-0) in order to extract the  $\mathcal{T}\text{-violating}$  $Re(\epsilon)$  parameter as the theoretical prediction for large time differences is  $R_2(\Delta t) \stackrel{\Delta t \gg \tau_s}{\longrightarrow} 1 - 4Re(\epsilon)$  and  $R_4(\Delta t) \stackrel{\Delta t \gg \tau_s}{\longrightarrow} 1 + 4Re(\epsilon)$ .



<span id="page-2-0"></span>Fig. 1. Expected behaviour of the transition probability ratios  $R_2$  and  $R_4$  as a function of proper decay times difference  $\Delta t$  as simulated for  $10 fb^{-1}$  of KLOE-2 data. Figure adapted from [\[1\]](#page-4-0).

#### 3. Experimental realization at KLOE-2 and DAΦNE

The DAΦNE  $\phi$ -factory is an electron-positron collider operating at the The DATNE  $\varphi$ -ractory is an electron-positron confluer operating at the energy of the  $\phi$  resonance peak ( $\sqrt{s} \approx 1020 \text{MeV}$ ) and predominantly producing  $\phi$  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 [\[6\]](#page-4-5).

As shown in the previous section, a direct test of  $\mathcal T$  symmetry at KLOE-2 requires ability to reconstruct two types of events:  $K_S K_L \rightarrow \ell^{\pm} \pi^{\mp} \nu \, 3 \pi^0$ and  $K_S K_L \to \pi \pi \ell^{\pm} \pi^{\mp} \nu$ . For construction of time-depedent decay distributions, kaon proper decay times should be determined with resolution of the

order of 1  $\tau_S$ . In 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  $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$  decay, however, is a challenging reconstruction task as only neutral particles are involved and the only recorded information on this process are the  $\gamma$  hits in the EMC. For this decay a new reconstruction method was prepared for KLOE-2.





<span id="page-3-0"></span>Fig. 2. Scheme of the  $K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$  decay vertex reconstruction in cross-section view of the KLOE EMC (grey ring).

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

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

As the K<sup>L</sup> 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,](#page-3-0) right). Although only 4  $\gamma$  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  $K_L \rightarrow 3\pi^0$  events. Resolution of proper  $K_L$  decay time was estimated for several regions of the decay vertex distance from the interaction point. Fig. [3](#page-4-6) shows the resulting resolution which is at the level of  $\sim$  2  $\tau_s$  and remains constant with increasing  $K<sub>L</sub>$  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.



<span id="page-4-6"></span>Fig. 3. Resolution of proper  $K_L$  decay time reconstructed for  $K_L \rightarrow 3\pi^0$  with the new method as a function of the decay vertex distance from the  $\phi$  decay point (IP).

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