STUDY OF THE $K_S K_L \rightarrow \pi \ell \nu 3\pi^0$ 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 ($T$) independently of $CP$ violation. This is achieved by a comparison of probabilities for a transition between flavour and $CP$-definite states and its inverse obtained through exchange of initial and final states. As such, a test requires the reconstruction of the $K_L \rightarrow 3\pi^0$ decay accompanied by $K_S \rightarrow \pi^\pm \ell^\mp \nu$ 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 $O(1\tau_S)$.

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

1. Introduction

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

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

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 $\ell^+, \ell^-$) 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 $K_+$ ($\mathcal{CP} = 1$) and $K_-$ ($\mathcal{CP} = -1$), 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>
<thead>
<tr>
<th>Transition</th>
<th>$\mathcal{T}$-conjugate</th>
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<tbody>
<tr>
<td>$K^0 \rightarrow K_+$ ($\ell^-, \pi\pi$)</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>

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

\(^2\) Only $3\pi^0$ is a pure $\mathcal{CP} = -1$ state.
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proportional up to a constant:

$$R_2(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K^0(\Delta t)]} \sim \frac{I(\ell^-, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^+; \Delta t)},$$  \hspace{1cm} (2)

$$R_4(\Delta t) = \frac{P[\bar{K}^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to \bar{K}^0(\Delta t)]} \sim \frac{I(\ell^+, 3\pi^0; \Delta t)}{I(\pi\pi, \ell^-; \Delta t)},$$ \hspace{1cm} (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 $T$ symmetry violation. At KLOE-2, the asymptotic behaviour of these ratios can be measured (see Fig. 1) in order to extract the $T$-violating $\text{Re}(\epsilon)$ parameter as the theoretical prediction for large time differences is $R_2(\Delta t) \overset{\Delta t \gg \tau_S}{\longrightarrow} 1 - 4 \text{Re}(\epsilon)$ and $R_4(\Delta t) \overset{\Delta t \gg \tau_S}{\longrightarrow} 1 + 4 \text{Re}(\epsilon)$.

![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].](image)

3. Experimental realization at KLOE-2 and DAΦNE

The DAΦNE $\phi$-factory is an electron–positron collider operating at the energy of the $\phi$ resonance peak ($\sqrt{s} \approx 1020$ 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].
As shown in the previous section, a direct test of $T$ 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 $K_S K_L \to \pi^0 \ell^\pm \pi^\mp \nu$. For construction of time-dependent decay distributions, kaon proper decay times should be determined with resolution of the order of $1/\tau_S$. 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 $\gamma$ 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 6 $\gamma$ 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 $\gamma$ 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 $\gamma$ hit constitute a system of equations

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

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 $\gamma$ 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 $K_L \to 3\pi^0$ 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 $\sim 2\,\tau_S$ 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 $K_L \to 3\pi^0$ with the new method as a function of the decay vertex distance from the $\phi$-decay point (IP).](image)

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 7th 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 HOM-ING PLUS BIS/2011-4/3.
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