

# Test of discrete symmetries in transitions with entangled neutral kaons at KLOE-2

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**Abstract.** The KLOE-2 experiment at the INFN Laboratori Nazionali di Frascati (LNF) completed its data-taking at the  $e^+e^-$  DAΦNE collider, which implements an innovative collision scheme based on a crab-waist configuration, and achieved the integrated luminosity of more than  $5 \text{ fb}^{-1}$ . KLOE-2 represents the continuation of KLOE with an upgraded detector and an extended physics program which includes, among the main topics, neutral kaon interferometry and test of discrete symmetries. Entangled neutral kaon pairs produced at DAΦNE are a unique tool to test discrete symmetries and quantum coherence at the utmost sensitivity, strongly motivating the experimental searches of possible CPT violating effects, which would constitute an unambiguous signal of New Physics. The status of the test of Time reversal and CPT symmetry in  $\phi \rightarrow K_S K_L \rightarrow \pi\nu, 3\pi^0, (2\pi)$  decays with KLOE and KLOE-2 data will be discussed.

## 1. Introduction

DAΦNE, the Frascati  $\phi$ -factory, is an  $e^+e^-$  collider working at a center of mass energy of  $\sqrt{s} \sim 1020 \text{ MeV}$  [1], corresponding to the peak of the  $\phi$  resonance. The KLOE experiment at DAΦNE completed its first data taking campaign in March 2006 with a total integrated luminosity of  $\sim 2.5 \text{ fb}^{-1}$ , corresponding to a production of  $\sim 7.5 \times 10^9$   $\phi$ -mesons and  $\sim 2.5 \times 10^9$   $K_0\bar{K}_0$  pairs. After the KLOE run, DAΦNE has been upgraded implementing an innovative collision scheme based on a crab-waist configuration [2]. The KLOE-2 experiment [3], aiming to extend the physics program of its predecessor, completed the data-taking in March 2018 at the upgraded DAΦNE with an improved detector. The total integrated luminosity collected was  $\sim 5.5 \text{ fb}^{-1}$ , as originally planned. The KLOE-2 physics program includes neutral kaon interferometry and tests of discrete symmetries and quantum mechanics.

The properties of the neutral kaon system are directly related to the CP, T and CPT symmetries and provide the potential of performing very precise tests and to search for violation effects. The quantum entanglement of neutral kaons produced by the  $\phi$  decay, allows for a large number of quantum interferometry studies. The KLOE experiment, is the only experiment at  $\phi$ -factory's, so has the unique possibility to study the entangled neutral Kaon pairs and to give a large contribution to the knowledge of kaon physics and related discrete symmetries violation.

## 2. The KLOE-2 experiment

The original KLOE detector consists of a large cylindrical drift chamber (DC) [4], which provides excellent momentum and vertex reconstruction accuracy for charged particles. DC is surrounded

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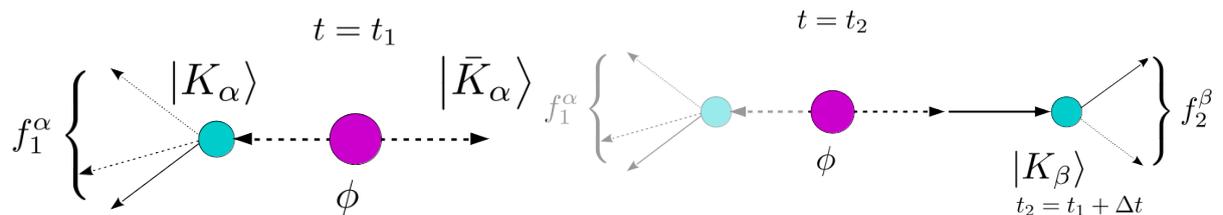
by a lead-scintillating fiber electromagnetic calorimeter (EMC) [5]. The energy deposits of charged and neutral particles in the calorimeter are measured with very good time resolution, allowing particle identification with time-of-flight (TOF) techniques. A superconducting coil around the EMC provides a 0.52 T axial field.

The upgrade of the KLOE detector was based on: i) an inner tracker (IT) made of cylindrical GEM for the improvement of tracking and decay vertex resolution close to the interaction point (IP)[6], ii) two  $e^+e^-$  tagging system for the  $\gamma\gamma$  physics at low and high lepton energy regimes [7, 8], a pair of crystal calorimeters inside the innermost part of the detector, close to IP, to increase the photon acceptance down to  $8^\circ$  [9], iii) a pair of scintillator/absorber detectors surrounding the beam pipe region [10] to improve acceptance and efficiency for photons and pions coming from neutral kaon decays.

Kaon physics is typically studied by tagging one the two kaons with a special decay/interaction of the other. This is the case of  $K_S$  tagged by the  $K_L$  interaction in the EMC calorimeter or the  $K_L$  tagged by the  $K_S$  decay near the IP. Nevertheless a different approach to the kaon physics is possible at  $\phi$ -factory, based on the observation of the time evolution of the system correlation. The quantum mechanics description of the  $\phi \rightarrow K_S K_L$  decay implies an anti-correlated initial state that evolves in time preserving this characteristics. This feature has been already exploited to perform several tests and measurements on the kaon system [11, 12]. Kaon correlation could be also used to tag CP or Flavor eigenstate during the time evolution of the initial state [13], as discussed in the next section.

### 3. Discrete symmetry tests in kaon transition amplitudes

The quantum correlation between the two neutral kaons allows the time-tagging of the initial state of one of the two by using the decay of the other as shown in fig. 1 (left). In the sketch the  $f_1^\alpha$  is the tagging decay observed at the time  $t_1$  that implies a well defined corresponding state for the undecayed kaon ( $\bar{K}_\alpha$ ) at the same time. Similarly the “tagged” kaon will be observed to decay in the final state  $f_2^\beta$  at the time  $t_2$  as sketched in fig. 1 (right). This decay will reveal the state of the second kaon as  $K_\beta$ , so the transition amplitudes between  $\bar{K}_\alpha$  and  $K_\beta$  could be derived from the observed time evolution between  $t_1$  and  $t_2$ .



**Figure 1.** Time evolution of the kaon system at the time of the first decay  $t_1$  in the final state  $f_1^\alpha$  (left) and at the time  $t_2$  of the second decay  $f_2^\beta$ . The entanglement between the two kaons allows to identify the state of the undecayed kaon at  $t_1$ . The observation of the decay at  $t_2$  allows to study the transition amplitudes between the initial and final state.

Different transition amplitudes can be studied with the corresponding choice of the kaon decay pairs. In the table 3 all possible transition amplitudes between flavor and  $CP$  eigenstates are related via the corresponding discrete symmetries. A comparison of the rates of neutral mesons transitions between their flavor and  $CP$  eigenstates allows for a model independent test of the T and CPT symmetries. Similar test has been performed already in the case of neutral B mesons obtaining the first direct evidence of T violation [14].

**Table 1.** Transition amplitudes connected via discrete symmetries.  $K_0\bar{K}_0$  and  $K_+K_-$  are Flavor and CP eigenstates, respectively.

Reference	T-conjug.	CP-conjug.	CPT conjug.
$K_0 \rightarrow K_+$	$K_+ \rightarrow K_0$	$\bar{K}_0 \rightarrow K_+$	$K_+ \rightarrow \bar{K}_0$
$K_0 \rightarrow K_-$	$K_- \rightarrow K_0$	$\bar{K}_0 \rightarrow K_-$	$K_- \rightarrow \bar{K}_0$
$\bar{K}_0 \rightarrow K_+$	$K_+ \rightarrow \bar{K}_0$	$K_0 \rightarrow K_+$	$K_+ \rightarrow K_0$
$\bar{K}_0 \rightarrow K_-$	$K_- \rightarrow \bar{K}_0$	$K_0 \rightarrow K_-$	$K_- \rightarrow K_0$

As stated previously the kaon states along the time evolution are identified by using the decay channel. The flavor eigenstates are identified by using the semileptonic decays  $K_0 \rightarrow \pi^- e^+ \nu$  and  $\bar{K}_0 \rightarrow \pi^+ e^- \bar{\nu}$  because the charge of the lepton emitted in the decay is connected with the sign of the intermediate W boson responsible for the decay at tree level. The CP eigenstate instead are tagged by using the fully hadronic decay mode in two ( $K_+ \rightarrow \pi^+ \pi^-$ ) or three pions ( $K_- \rightarrow 3\pi^0$ ). The observables related to T and CPT violation are defined as:

$$R_2(\Delta t) = \frac{P(K_0(0) \rightarrow K_-(\Delta t))}{P(K_-(0) \rightarrow K_0(\Delta t))} \sim \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^+ \Delta t)} \quad (1)$$

$$R_4(\Delta t) = \frac{P(\bar{K}_0(0) \rightarrow K_-(\Delta t))}{P(K_-(0) \rightarrow \bar{K}_0(\Delta t))} \sim \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^- \Delta t)} \quad (2)$$

$$R_2^{CPT}(\Delta t) = \frac{P(K_0(0) \rightarrow K_-(\Delta t))}{P(K_-(0) \rightarrow \bar{K}_0(\Delta t))} \sim \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^- \Delta t)} \quad (3)$$

$$R_4^{CPT}(\Delta t) = \frac{P(\bar{K}_0(0) \rightarrow K_-(\Delta t))}{P(K_-(0) \rightarrow K_0(\Delta t))} \sim \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^+ \Delta t)} \quad (4)$$

where  $I(f_1, f_2; \Delta t)$  denotes the number of recorded events characterized by a time-ordered pair of kaon decays  $f_1$  and  $f_2$  separate by an interval of proper kaon decay times  $\Delta t$ . A deviation of the asymptotic level of these ratios from unity for large transition times would be a T or CPT violation manifestation. Preliminary results on the time reversal symmetry tests are reported in the Fig. 2 where the distribution relative to eq. 1 and eq. 2 are shown.

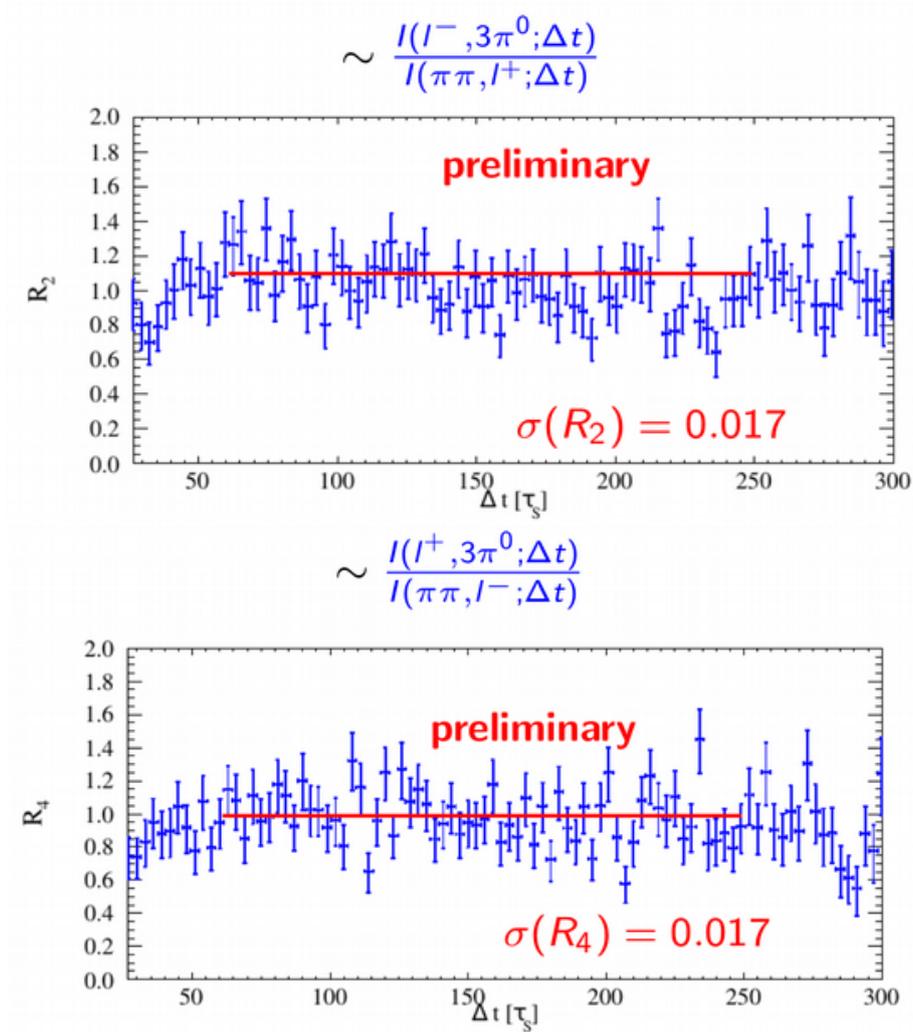
A more robust test on the CPT symmetry violation is shown in Fig. 3 where the double ratio  $R_2^{CPT}(\Delta t)/R_4^{CPT}(\Delta t)$  is shown. The double ratio is built from Eq. 3 and 4 and allows to cancel many systematic effect related to tracking, particles identification and decay vertex reconstruction.

#### 4. Conclusions

The data-taking finished in 2018 allows the KLOE-2 collaboration to access a unique data-set of order of  $8 \text{ fb}^{-1}$  of  $\phi$  decays. Among all the possible studies, the kaon quantum correlation, already studied with the old KLOE data-set, will be further explored as the presented study shows. The expected precision of  $10^{-3}$  on the double ration will be achievable when the full data-set will be analyzed and all the systematics will be carefully taken into account.

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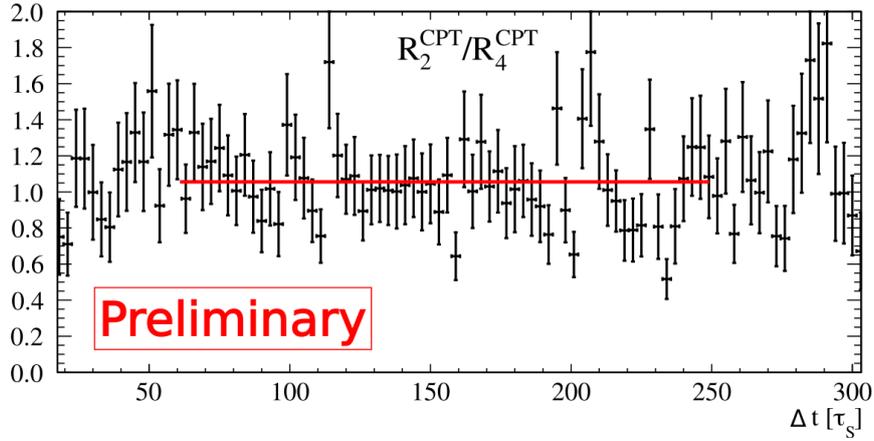


**Figure 2.** Preliminary distribution of the T-violation sensitive ratios of neutral kaon double decay rates as a function of kaon decay times difference ( $\Delta t$ ) as in Eq. 1 and Eq. 2. The statistical uncertainty of the asymptotic level of this observable for  $\Delta t \gg \tau_S$  (red line) is relative to the KLOE data-set ( $2 \text{ fb}^{-1}$ ) only.

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**Figure 3.** Preliminary distribution of the double ratio  $R_2^{CPT}(\Delta t)/R_4^{CPT}(\Delta t)$  of neutral kaon double decay rates as a function of kaon decay times difference ( $\Delta t$ ) defined in Eq. 3 and Eq. 4. This distribution is sensitive to CPT-violation for large  $\Delta t$ . The statistical uncertainty of the asymptotic level of this observable for  $\Delta t \gg \tau_S$  (red line) amounts to 0.011 with the KLOE data-set ( $2 \text{ fb}^{-1}$ ).

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