



Tests of discrete symmetries with the neutral kaon system at the KLOE and KLOE-2 experiments

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Abstract

The KLOE-2 experiment continues and extends the program of its predecessor KLOE in the field of discrete symmetry tests with the K meson system, among other studies which comprise light meson spectroscopy, dark matter searches and $\gamma\gamma$ physics. Together, KLOE and KLOE-2 have recorded the largest sample (almost 8 fb^{-1}) of e^+e^- collisions at the energy equal to ϕ meson mass, amounting to 2.4×10^{10} of produced ϕ mesons. We report on the latest results and ongoing analyses of KLOE and KLOE-2 concerning discrete symmetry tests and measurements of symmetry-violating observables. A measurement of the CPT violation sensitive asymmetry in semileptonic decays of K_S with 1.7 fb^{-1} of KLOE data will be presented, which improves the sensitivity w.r.t. previous measurements about twice. Moreover, status of direct tests of T and CPT in transitions of neutral kaons performed with the $\phi \rightarrow K_S K_L \rightarrow \pi e \nu$, $3\pi^0(2\pi)$ processes will be reported, followed by the search of the CP-violating decay $K_S \rightarrow 3\pi^0$ using the data recently acquired by KLOE-2.

Keywords Discrete symmetries · CPT · CP · Neutral kaons

1 Introduction

Flavoured neutral mesons constitute powerful physical systems for testing fundamental discrete symmetries and their combinations such as CP and CPT. Among them, neutral kaons are extensively used to search for manifestations of symmetry violations as the symmetries are easily translated to constraints on the properties of this system [1].

Despite numerous experiments conducted with neutral K mesons to date, the potential of this system is far from being exploited. The KLOE experiment has contributed to determination of the neutral kaon properties as well as a number of tests of the CP and CPT symmetries [2]. However, the dataset collected by KLOE is still analysed with a view to obtaining more precise results, e.g. on the charge asymmetry in the semileptonic K_S decays

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and performing new tests such as a first direct CPT test in transitions of neutral kaons. Moreover, the upgraded KLOE-2 detector has recently finished taking more than 5 fb^{-1} of data which will allow for enhancing the precision of searches for the CP-violating decay $K_S \rightarrow 3\pi^0$.

2 The KLOE and KLOE-2 experiments

KLOE and KLOE-2 operated at the DAΦNE ϕ -factory which collides electron and positron beams at $\sqrt{s} \approx 1020 \text{ MeV} = m_\phi$, producing predominantly ϕ mesons. Their decays into a pair of neutral kaons ($\text{BR}(\phi \rightarrow K^0 \bar{K}^0) \approx 34 \%$) are recorded by the KLOE setup consisting of a large ($R = 2 \text{ m}$) cylindrical drift chamber [3] surrounded by a sampling electromagnetic calorimeter with a coverage of 98 % of 4π [4]. KLOE-2 additionally features a cylindrical triple-GEM inner tracker [5] and calorimeters in the beamline region [6, 7] improving tracking and acceptance for particles at small polar angles. KLOE was taking data in the years 2001–2002 and 2004–2005, collecting 2.5 fb^{-1} of ϕ decays. The KLOE-2 dataset was collected in 2014–2018 and amounts to over 5 fb^{-1} . Together, KLOE and KLOE-2 have provided the largest sample of $e^+e^- \rightarrow \phi$ events, corresponding to about 2.4×10^{10} of produced ϕ mesons.

3 Tests of CP and CPT with the charge asymmetry in K_S semileptonic decays

The charge asymmetry in the neutral kaon decays ($A_{S/L}$ for K_S and K_L respectively) is related to parameters violating CP, CPT and the $\Delta S = \Delta Q$ rule. While non-zero value of each of the asymmetries indicates CP violation, observation of a discrepancy between them would be a sign of CPT noninvariance.

The asymmetry in decays of K_L has been measured by the KTeV experiment with a precision of 10^{-5} [8]. The best result in case of K_S comes from the KLOE 2001–2002 measurement and its statistics-limited precision is 2 orders of magnitude below that of K_L [9]. Recently, the full dataset of KLOE was therefore used to determine A_S with a reduced statistical uncertainty.

K_S decay events were tagged by presence of a K_L interaction in the calorimeter. Semileptonic decays were selected with an analysis of particle time of flight from the decay point to the calorimeter. A certain amount of background was allowed in the final event samples to perform a MC-based event counting. Semileptonic K_S decays were counted in a selected region of the following kinematic variable: $M^2 = [E_{K_S} - E_\pi - E_\nu]^2 - p_e^2$, which allowed for good separation of the signal and background regions as shown in Fig. 1.

MC-simulated M^2 distributions for signal ($K_S \rightarrow \pi^\pm e^\mp \nu$) and major background components were fitted to the spectrum obtained from experimental data. The numbers of semileptonic decay events obtained from the fit were 34579 ± 251 for $K_S \rightarrow \pi^- e^+ \nu$ and 36874 ± 255 for $K_S \rightarrow \pi^+ e^- \bar{\nu}$, resulting in the following value of the charge asymmetry:

$$A_S = (-4.9 \pm 5.7_{\text{stat}} \pm 2.6_{\text{syst}}) \times 10^{-3}. \quad (1)$$

The above result combined with the previous one also determined by KLOE constitutes the most precise measurement of A_S available to date:

$$A_S = (-3.7 \pm 5.0_{\text{stat}} \pm 2.6_{\text{syst}}) \times 10^{-3}. \quad (2)$$

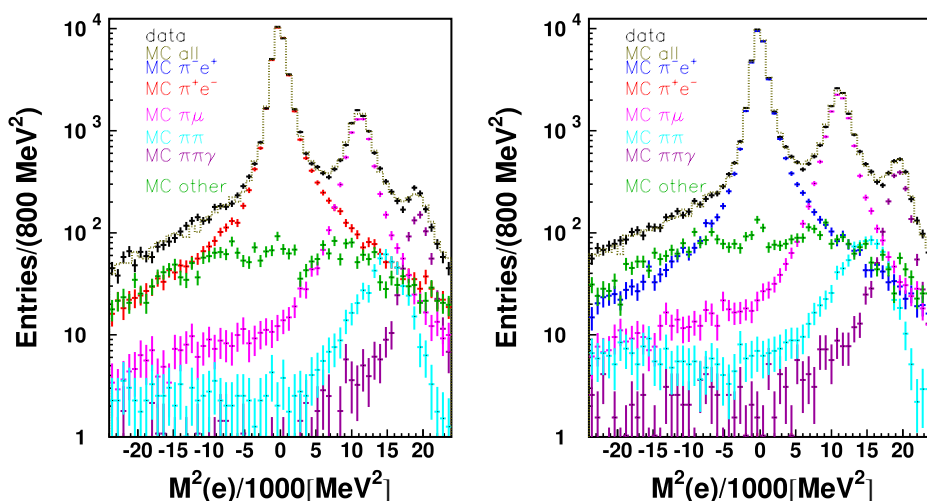


Fig. 1 Distributions of the kinematic variable used to separate signal and background for $K_S \rightarrow \pi^+ e^- \bar{\nu}$ (left) and $K_S \rightarrow \pi^- e^+ \nu$ (right) event counting. MC-simulated distributions for signal and major background components (color points) are normalized to experimental data (black histogram) to extract the number of signal events with each lepton charge [10]

4 Direct test of T and CPT in transitions of neutral kaons

A comparison of the rates of neutral mesons transitions between their flavour and CP eigenstates allows for a model independent test of the T and CPT symmetries [11, 12]. Such a test, to date performed only in the case of neutral B mesons where it delivered the first direct evidence of T violation [13], is pursued with the $K^0 \bar{K}^0$ system at KLOE-2.

In this novel test, quantum entangled meson pairs are used to identify the initial state of a particle transition by the decay of its entangled partner, while the final state is tagged by semileptonic and hadronic decays into two and three pions. Two T-violating observables are determined as ratios of the rates of two classes of processes identified in the KLOE dataset: $K_S K_L \rightarrow \pi^\pm e^\mp \nu, 3\pi^0$ and $K_S K_L \rightarrow \pi^+ \pi^-, \pi^\pm e^\mp \nu$:

$$R_2(\Delta t) = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow K^0(\Delta t)]} \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+ \pi^-, \pi^- e^+ \nu; \Delta t)}, \quad (3)$$

$$R_4(\Delta t) = \frac{P[\bar{K}^0(0) \rightarrow K_-(\Delta t)]}{P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]} \sim \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+ \pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}, \quad (4)$$

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 Δt [11]. A deviation of the asymptotic level of these ratios from unity for large transition times would be a T-violation manifestation.

Moreover, the concept of such test can be generalized to test the CPT symmetry through determination of the asymptotic level of the following double ratio:

$$\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{P[K^0(0) \rightarrow K_-(\Delta t)]/P[K_-(0) \rightarrow \bar{K}^0(\Delta t)]}{P[\bar{K}^0 \rightarrow K_-(\Delta t)]/P[K_-(0) \rightarrow K^0(\Delta t)]} \Delta t \gg \tau_S \quad 1 - 8\Re\delta_K - 8\Re x_-, \quad (5)$$

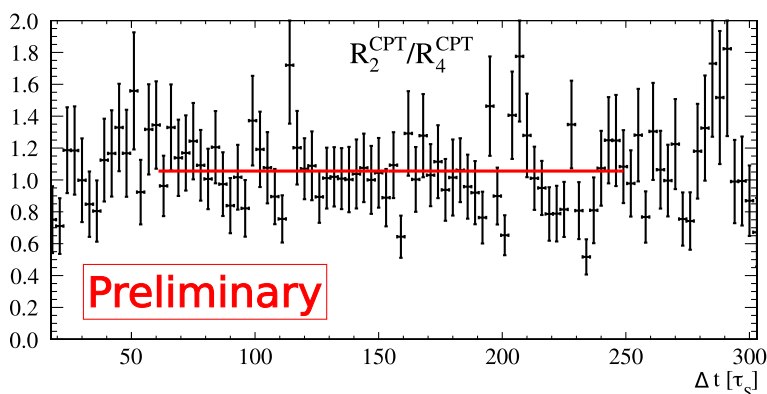


Fig. 2 Preliminary distribution of the CPT-violation sensitive double ratio of neutral kaon double decay rates as a function between entangled kaon decay times' difference (Δt). The statistical uncertainty of the asymptotic level of this observable for $\Delta t \gg \tau_S$ (red line) amounts to 0.011 with the KLOE dataset

where the δ_K and x_- are parameters violating the CPT symmetry in $K^0\bar{K}^0$ mixing and the $\Delta S = \Delta Q$ rule, respectively. This double ratio constitutes a robust CPT-violation sensitive observable [12] which has never been measured to date.

The analysis tools required to determine both the above T-violation sensitive ratios and the CPT-violation sensitive double ratio are prepared and tested using the KLOE dataset. A preliminary distribution of the ratio defined in (5) obtained with 1.7 fb^{-1} of KLOE data, is presented in Fig. 2. Although the uncertainty on the asymptotic level of these observables available with KLOE data is only at the percent level, the analysis is prepared with a view to its application to the larger sample of KLOE-2, which will allow for statistically significant tests of T and CPT at the 10^{-3} level of precision.

5 Search for the CP-violating $K_S \rightarrow 3\pi^0$ decay

Another class of CP-violating phenomena in the neutral kaon system is constituted by the decays of K_S into a CP-asymmetric state with three pions. While the $K_S \rightarrow \pi^+\pi^-\pi^0$ process contains both CP-violating and conserving amplitudes, observation of the $K_S \rightarrow 3\pi^0$ decay would be a clear signature of CP violation. The present best limit was set by KLOE at $\text{BR}(K_S \rightarrow 3\pi^0) < 2.6 \times 10^{-8}$ [14], still almost an order of magnitude lower than the precision of the Standard Model prediction (1.9×10^{-9}). Therefore, the search for $K_S \rightarrow 3\pi^0$ is already performed using the recently collected 5 fb^{-1} of KLOE-2 data. The larger data sample and data analysis optimized with respect to the previous measurement are expected to increase the sensitivity for this rare decay beyond the level of 10^{-8} .

6 Summary and perspectives

The measurements of the KLOE detector have recently delivered the most precise result on the charge asymmetry in the semileptonic decays of the short-lived neutral K meson, consistent with CPT conservation within the total uncertainty of 5.6×10^{-3} . The larger dataset collected recently by the upgraded KLOE-2 detector is expected to further improve

the precision of this measurement to the level of 3×10^{-3} . The datasets of KLOE and KLOE-2 are also used to perform first direct tests of the T and CPT symmetries in transitions of neutral kaons, expected to reach the precision of 10^{-3} . Finally, the search for the CP-violating decay $K_S \rightarrow 3\pi^0$ is performed with the KLOE-2 dataset. The expected sensitivity to this process should allow KLOE-2 to approach the level of the present Standard Model prediction for $\text{BR}(K_S \rightarrow 3\pi^0)$.

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