TESTS OF DISCRETE SYMMETRIES AND QUANTUM COHERENCE WITH NEUTRAL KAONS AT THE KLOE-2 EXPERIMENT*

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The KLOE-2 detector records decays of quantum-entangled pairs of neutral kaons produced in decays of ϕ mesons provided by the DAΦNE accelerator at the Laboratori Nazionali di Frascati, Italy. This system allows for a broad range of studies of fundamental discrete symmetries including tests which are only feasible with entangled neutral mesons. This work reports on the Lorentz non-invariance and CPT violation searches with the $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ process in the framework of the Standard Model Extension. Moreover, status and results of quantum coherence tests with the same process are discussed. Finally, the status of ongoing direct tests of T and CPT in neutral kaon transitions is presented. For each of the reported studies, perspectives are discussed for the KLOE-2 experiment, which is presently taking data.

1. Introduction

Systems of flavoured neutral mesons have long proven to constitute an excellent ground for studies of the fundamental discrete symmetries of Nature as conservation of the latter can be easily translated to constraints on the properties of such systems. Among them, neutral kaons are of special importance as the value of the mass difference between K^0 and $\bar{K}^0$ state enables the use of quantum-entangled pairs of neutral K mesons to observe a range of quantum intereference phenomena. Such interferometric measurements may also be used to design tests of discrete symmetries and quantum

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mechanics as has been shown by the KLOE experiment, which to date is the sole experimental setup where $K^0\bar{K}^0$ pairs are available in a quantum entangled state, provided by the DAΦNE ϕ-factory. Presently, the physics programme is continued by the KLOE-2 detector. This work reports on the recent tests of both discrete symmetries and quantum coherence performed by KLOE and the perspectives for KLOE-2 results.

2. The KLOE-2 setup at the DAΦNE ϕ-factory

The KLOE-2 detector records decays of ϕ mesons produced in e^+e^- collisions by the DAΦNE collider operating in the National Laboratories of Frascati in Italy. The detection setup common for KLOE and KLOE-2 consists of a cylindrical drift chamber (DC) [1] and a sampling electromagnetic calorimeter (EMC) surrounding it with a coverage of 98% of 4π [2]. The DC uses a light gas mixture to minimize kaon regeneration and its size with an outer radius of 2 m is driven by the need to detect a large part (40%) of decays of the K_L mesons, whose mean path in KLOE is about 3.4 m. The calorimeter provides a good timing resolution which is used to reconstruct the $K_L \to 3\pi^0 \to 6\gamma$ decays based on the γ interaction points in the EMC [3]. Additionally, the KLOE-2 uses a novel Inner Tracker device based on 4 layers of Cylindrical Gas Electron Multiplier detector aiming at improving tracking and vertexing resolution close to the interaction point [4].

3. Search for CPT and Lorentz symmetry violation with the $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ process

In the framework of the Standard Model Extension (SME) [5] and the anti-CPT theorem [6], violation of CPT must be associated to the Lorentz non-invariance, which allows to test CPT by searching for Lorentz symmetry-violating effects. In the neutral K meson system, the latter would be manifested by a dependence of the usual CPT-related δ parameter [7] on the Lorentz factor γ_K and momentum direction $\vec{\beta}_K$ of a kaon

$$\delta_K \simeq i \sin \phi_{SW} e^{i\phi_{SW}} \gamma_K \left(\Delta a_0 - \vec{\beta}_K \Delta \vec{a} \right) / \Delta m \,, \qquad (1)$$

where Δa_μ denote the parameters of the SME Lagrangian part and ϕ_{SW} is the so-called superweak phase.

Experimentally, δ_K as a function of the kaon momentum direction can be extracted from a double decay amplitude for quantum-entangled $K_S K_L$ pairs with both kaons decaying into the $\pi^+\pi^-$ final state

$$I(\Delta \tau) \sim e^{-\Gamma|\Delta\tau|} \left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re e \left(\eta_1 \eta_2^* e^{-i\Delta m \Delta\tau} \right) \right] , \quad (2)$$

where the $\eta_{1(2)}$ amplitudes are dependent on $\delta(\vec{p}_K)$ and $\Delta\tau$ denotes the time difference between both kaon decays.

To this end, $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ events were selected from the 1.7 fb^{-1} of data recorded by KLOE. To account for direction dependence, the events were divided into two angular subsamples based on the projection of the momentum of the more energetic of two kaons on the ϕ direction in the laboratory reference frame. Consequently, daily movement of the laboratory was expressed in the frame of fixed stars and the data sample was further split into 4 intervals of sidereal time. For each of the eight obtained subsamples of $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ events, the double decay rate (Eq. (2)) was fit simultaneously in order to extract the Δa_μ SME parameters of the kaon sector. The results, presented in Table I, reach the expected sensitivity at the level of 10^{-18} GeV [8], which is several orders of magnitude more precise than results obtained with other neutral meson systems [9]. Moreover, further improvement is expected with the KLOE-2 detector due to its goal integrated luminosity of 5 fb^{-1} as well as the enhanced tracking capabilities. Expected KLOE-2 statistical uncertainty is shown in Table I.

TABLE I

Values of the Lorentz symmetry-violating SME parameters measured by the KLOE experiment with 1.7 fb^{-1} of data [8]. The rightmost column presents statistical uncertainty expected with data taken by the KLOE-2 experiment and 5 fb^{-1} of data.

SME parameter	KLOE measurement	Expected KLOE-2 uncertainty
Δa_0	$(-6.0 \pm 7.7_{\text{stat}} \pm 3.1_{\text{syst}}) \times 10^{-18}$ GeV	$\pm 2.2_{\text{stat}} \times 10^{-18}$ GeV
Δa_X	$(0.9 \pm 1.5_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-18}$ GeV	$\pm 0.4_{\text{stat}} \times 10^{-18}$ GeV
Δa_Y	$(-2.0 \pm 1.5_{\text{stat}} \pm 0.5_{\text{syst}}) \times 10^{-18}$ GeV	$\pm 0.4_{\text{stat}} \times 10^{-18}$ GeV
Δa_Z	$(3.1 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-18}$ GeV	$\pm 0.5_{\text{stat}} \times 10^{-18}$ GeV

4. Search for quantum decoherence with $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$

Interferometric studies of the double decay rate for a pair of neutral kaons decaying into $\pi^+\pi^-\pi^+\pi^-$ also enable a test of Quantum Mechanics through a measurement of decoherence level for the entangled K mesons. Such decoherence, which could occur after the $\phi \to K^0\bar{K}^0$ decay according to the hypothesis of Furry [10], can be parametrised by inserting a ζ decoherence parameter before the interference term in the double decay amplitude (for the $K^0\bar{K}^0$ basis)

$$I(\pi^+\pi^-, \pi^+\pi^-, \Delta t) = \frac{N}{2}\Big[\left|\left\langle\pi^+\pi^-, \pi^+\pi^-\left|K^0\bar{K}^0(\Delta t)\right\rangle\right|^2\right.$$
$$+ \left|\left\langle\pi^+\pi^-, \pi^+\pi^-\left|\bar{K}^0 K^0(\Delta t)\right\rangle\right|^2$$
$$-(1-\zeta_{0\bar{0}})\cdot 2\Re\left(\left\langle\pi^+\pi^-, \pi^+\pi^-\left|K^0\bar{K}^0(\Delta t)\right\rangle\right.\right.$$
$$\left.\left.\left\langle\pi^+\pi^-, \pi^+\pi^-\left|\bar{K}^0 K^0(\Delta t)\right\rangle^*\right)\right], \tag{3}$$

where N is a normalization constant. Similarly, a ζ_{SL} parameter is defined for the $\{K_{\mathrm{S}}, K_{\mathrm{L}}\}$ basis.

Any possible quantum decoherence would, therefore, manifest itself as a reduction of the dip in the double decay rate for $\Delta t \approx 0$. This is caused by a destructive interference which prevents both kaons from decaying into the same final state at the same moment.

Both ζ_{SL} and $\zeta_{0\bar{0}}$ (for which sensitivity is naturally higher due to CP suppression in the decay channel) were extracted by KLOE with a fit to the double decay rate for a sample of $\phi \to K_{\mathrm{S}}K_{\mathrm{L}} \to \pi^+\pi^-\pi^+\pi^-$ decays displayed in the left panel of Fig. 1. The measurement yielded no observation of decoherence as the following values were obtained [11]:

$$\zeta_{0\bar{0}} = (1.4 \pm 9.5_{\mathrm{stat}} \pm 3.8_{\mathrm{syst}}) \times 10^{-7}, \tag{4}$$
$$\zeta_{\mathrm{SL}} = (0.3 \pm 1.8_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}}) \times 10^{-2}. \tag{5}$$

Even though the above results significantly improve previous measurements with neutral K [12] and B mesons [13], the factors limiting sensitivity comprise statistical uncertainty as well as Δt resolution of the interference region ($\Delta t \approx 0$), and a residual background component of the non-resonant
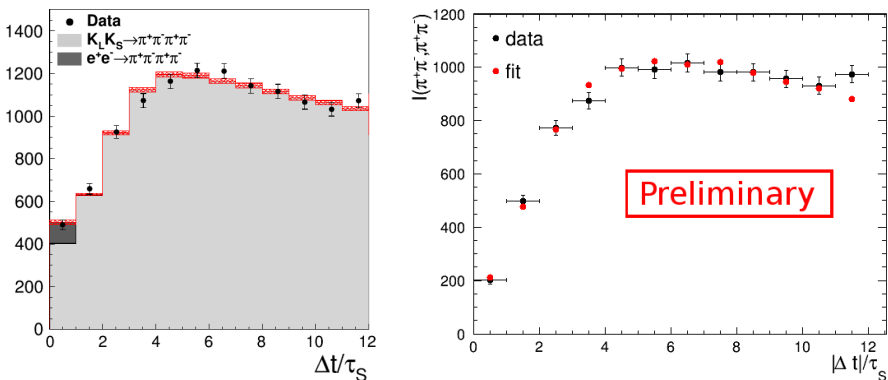

Fig. 1. Fits to double decay rates for $K_{\mathrm{S}}K_{\mathrm{L}} \to \pi^+\pi^-\pi^+\pi^-$ as a function of time difference between kaon decays obtained with published KLOE data analysis (left) [11] and a preliminary result of refined analysis (right) where an improved reproduction of the interference pattern for $\Delta t \approx 0$ is visible.

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$. The same dataset is, therefore, presently reanalised with a refined event selection which allows for a better reproduction of the interference pattern as shown in the preliminary distribution in the right panel of Fig. 1. Additionally, KLOE-2 data will bring a further improvement due to the use of new Inner Tracker subdetector.

5. Test of time-reversal and CPT symmetry in neutral kaon transitions with $\phi \to K_S K_L \to \pi e \nu \, 3\pi^0 \, (2\pi)$ decays

A novel concept of direct tests of discrete symmetries in neutral kaon transitions is presently pursued at KLOE-2 for the T and CPT symmetries. The test uses kaon transitions between their pure flavour $\{K^0, \bar{K}^0\}$ and CP-definite states $\{K_+, K_-\}$ and is based on a comparison between rates of processes like $K^0 \to K_-$ and their time-reversal conjugates obtained by an exchange of initial and final states [14, 15].

The kaon states are identified by semileptonic decays $K^0 \to \pi^- e^+ \nu$ and $\bar{K}^0 \to \pi^+ e^- \bar{\nu}$ as well as hadronic decays into two $(K_+ \to \pi^+\pi^-)$ and three pions $(K_- \to 3\pi^0)$. The initial state of the kaon in the compared transitions is inferred from the decay of its quantum-entangled partner, a technique which is only possible at DAΦNE in the case of neutral K mesons.

The $K_L \to 3\pi^0 \to 6\gamma$ decay involving only neutral particles is reconstructed using solely information on the photon interactions in the KLOE EMC with a trilateration-based technique specially devised for this study [3]. The event selection and reconstruction procedures, which will be applied to the dataset of KLOE-2, are currently being prepared and tested with the data already recorded by KLOE. Figure 2 presents preliminary distributions of rates of events corresponding respectively to the transitions $K^0 \to K_-$ and $K_- \to \bar{K}^0$, whose ratio $R_{2,\text{CPT}}^{\exp}(\Delta t) \sim P[K^0 \to K_-]/P[K_- \to \bar{K}^0]$ constitutes one of the observables of the CPT test[1].

An especially robust observable of the CPT symmetry test in transitions of neutral kaons is a ratio of the aforementioned CPT-violating ratios $R_{2,\text{CPT}}^{\exp}$ and $R_{4,\text{CPT}}^{\exp}(\Delta t) \sim P[\bar{K}^0 \to K_-]/P[K_- \to K^0]$ expressed as a function of the kaons' decay time difference. It was shown that the asymptotic value of this ratio in the region of $\Delta t \gg \tau_S$ (where τ_S denotes lifetime of K_S) is related to the CPT-violating parameters in the following way [15]:

$$\frac{R_{2,\text{CPT}}^{\exp}(\Delta t \gg \tau_S)}{R_{4,\text{CPT}}^{\exp}(\Delta t \gg \tau_S)} = 1 - 8\Re\delta - 8\Re x_- \,. \tag{6}$$

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[1] The reader is referred to [14] and [15] for a complete definition of observables for the T and CPT tests respectively.
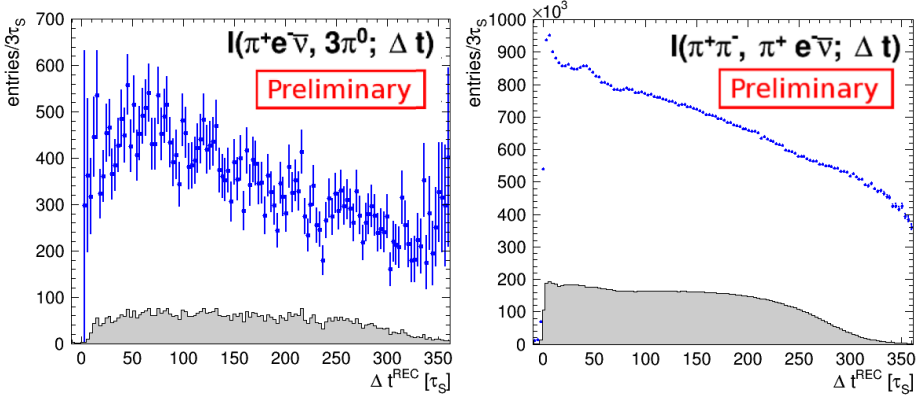
Fig. 2. (Colour on-line) Distributions of double decay rates as a function of kaon decay times difference for two chosen processes entering the determination of the asymmetries used in the direct T and CPT tests. Filled grey histograms present raw spectra, while the ones corrected for selection efficiency are marked with points.

A measurement of the asymptotic value of this CPT-violation sensitive double ratio is one of the objectives of KLOE-2. Figure 3 presents a preliminary result obtained with the KLOE dataset with an integrated luminosity of 1.7 fb^{-1}.
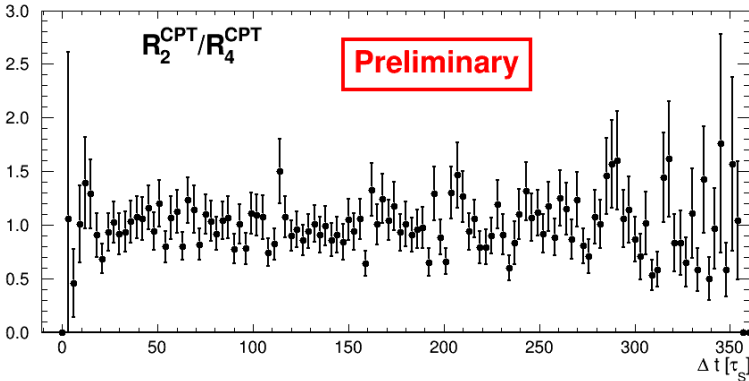
Fig. 3. Preliminary distribution of the CPT-asymmetric double ratio $R_{2,\mathrm{CPT}}^{\mathrm{exp}}/R_{4,\mathrm{CPT}}^{\mathrm{exp}}$ obtained with the KLOE data.

6. Summary and perspectives

Although the KLOE detector has already provided numerous contributions to the tests of fundamental discrete symmetries such as the CPT and the Lorentz symmetries, and the foundations of Quantum Mechanics through decoherence searches, KLOE data are still exploited to provide more precise

results as in the case of the decoherence parameter estimation. Moreover, a novel test of time reversal and CPT symmetries is in progress using the data collected by the KLOE-2 detector, which is presently in operation. KLOE-2 will bring not only larger statistics of at least 5 fb^{-1} but also improved event reconstruction due to new detector components such as the Inner Tracker. These factors are expected to improve sensitivity of all the reported tests.

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