CPT and Lorentz symmetry tests with entangled neutral kaons at KLOE/KLOE-2

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Abstract. The KLOE experiment at the DAΦNE ϕ-factory of the INFN Frascati Laboratory collected data corresponding to 2.5 fb^{-1} of integrated luminosity. Neutral kaon pairs produced in phi-meson decays offer a unique possibility to perform tests of fundamental discrete symmetries. The entanglement of the two kaons is exploited to search for possible violation of CPT symmetry and Lorentz invariance in the context of the Standard-Model Extension (SME) framework. A new approach to the analysis of $\phi \to K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$ events has been adopted allowing us to independently measure all four CPT violating parameters Δa_μ appearing for neutral kaons in the SME. The final KLOE results on Δa_μ will be presented. These are presently the most precise measurements in the quark sector of the SME.

1. Introduction

The invariance under CPT operation, the combined action of charge conjugation (C), parity reflection (P), and time-reversal (T), is fundamental in the framework of any quantum field theory. CPT is also one of the best tested symmetries having passed very stringent and diverse experimental tests (eg. $|m_{K^0} - m_{\overline{K^0}}/m_{av}| < 6 \times 10^{-19}$ [1]). As a consequence of Lorenz invariance, unitarity and locality of quantum field theory CPT may be however violated in the presence of quantum gravity effects (QG). In several QG models CPT can be violated via some mechanism which violates also standard Quantum Mechanics (QM) [2, 3], eg. causing decoherence of an entangled quantum state. As a consequence the quantum mechanical operator generating CPT transformations cannot be consistently defined [4]. CPT symmetry may be violated also through spontaneous breaking of Lorentz symmetry [5, 6] or locality [7] of interactions. In these cases the well-defined generator of the CPT symmetry does not commute with the effective Hamiltonian of the system [2]. On phenomenological grounds the CPT and Lorentz symmetries violation induced by quantum gravity effects is expected to be of the order of $\sim 10^{20}$ GeV, however they give rise to observable effects also in the low energy regime, particularly in the entangled neutral meson systems [8]. These effects have been sought inter alia in the B mesons system by the BaBar collaboration [9] and in the neutral kaon system by the KLOE experiment operating at the DAΦNE ϕ-factory. KLOE has provided best upper limits for phenomenological parameters describing CPT violation by decoherence of entangled neutral kaons [10] and by violation of the Lorentz symmetry [11] occurring within the framework of Standard Model Extension (SME) which will be discussed in this article.

2. Test of CPT and Lorentz symmetries with the KLOE detector

The KLOE experiment operates at the DAΦNE e^+e^- collider working at a center of mass energy of about 1020 MeV. Positron and electron beams collide at an angle of π-25 mrad, producing ϕ mesons with non-zero momentum in the horizontal plane, $|p_\phi| \sim 15$ MeV. In the KLOE reference frame [11]. The KLOE detector consists of an about 3.3 long cylindrical drift chamber with diameter equal to about 4 m, which is surrounded by the electromagnetic calorimeter. The detectors are placed in an axial magnetic field of superconducting solenoid equal to $B = 0.52$ T. The KLOE drift chamber [12] provides tracking in three dimensions with resolution in the bending plane about 200 μm, resolution on the z-coordinate measurement of about 2 mm and of 1 mm on the decay vertex position. Momentum of the particle is determined with a fractional accuracy $\sigma_p/p = 0.4\%$ for polar angles larger than 45° [13]. The KLOE electromagnetic calorimeter [14] consists of a barrel built out of 24 trapezoidal shaped modules and two endcaps. Each of the modules is built out of 1 mm scintillating embedded in 0.5 mm lead foils, and it is read out from both sides by set of photomultipliers. This detector allows for measurements of energy and time with accuracies of $\sigma_E/E = 5.7\%/\sqrt{E[\mathrm{GeV}]}$ and $\sigma(t) = 57\mathrm{ps}/\sqrt{E[\mathrm{GeV}]} \oplus 100$ ps, respectively. Analysis of the signal amplitude distribution provides also the determination of the point where the particle hit the calorimeter module [13]. Neutral kaons from ϕ meson decays are produced in a coherent quantum state:

$$|i\rangle = N\left(|K_S,\vec{p_1}\rangle\,|K_L,\vec{p_2}\rangle - |K_L,\vec{p_1}\rangle\,|K_S,\vec{p_2}\rangle\right)\ , \tag{1}$$

where $\vec{p_1}$ and $\vec{p_2}$ denote the kaon momenta and N is a normalization factor expressed in terms of the CP impurities ϵ_S and ϵ_L: $N = \sqrt{(1+|\epsilon_S|^2)(1+|\epsilon_L|^2)}/2(1-\epsilon_S\epsilon_L)$. Due to the quantum entanglement of the two neutral kaons their decays are correlated. Thus, the kaons double differential rate of decay into two final states $f_1$and f_2 contains characteristic time interference term [15]:

$$I(f_1,f_2,\Delta t) \sim |\eta_1|^2 e^{-\Gamma_L\Delta t} + |\eta_2|^2 e^{-\Gamma_S\Delta t} - 2|\eta_1|^2|\eta_2|^2 e^{-\frac{(\Gamma_L+\Gamma_S)}{2}\Delta t}\cos(\Delta m\Delta t + \phi_2 - \phi_1) \tag{2}$$

where Δt denotes the proper decay times difference of kaons and η_1 and η_2 are the following decay amplitude ratios: $\eta_i = |\eta_i|e^{i\phi_i} = \frac{\langle f_i|T|K_L\rangle}{\langle f_i|T|K_S\rangle}$. Γ_L and Γ_S denote widths of K_L and K_S meson, respectively. The decay intensities of entangled kaons appear to be very sensitive to any CPT violating effect at the level of the interesting Planck scale region, presently unreachable in other similar systems [15]. If both kaons decay to the same final state (e.g. $\pi^+\pi^-$) the interference pattern in Eq. 2 is very sensitive to any deviation from unity of the ratio η_1/η_2 in the interference region of $\Delta t \approx 0$. These deviations may be present due to the CPT violation which in the framework of SME manifests to lowest order only in the CPT violating parameter $\delta_K = (\epsilon_S - \epsilon_L)/2$ and exhibits a dependence on the 4-momentum of the kaon:

$$\delta_K \approx i\sin\phi_{SW} e^{i\phi SW}\gamma_K(\delta a_0 - \vec{\beta_K}\cdot\Delta\vec{a})/\Delta m\ , \tag{3}$$

where ϕ_{SW} is the superweak phase, γ_K and $\vec{\beta_K}$ are the boost factor and velocity of kaon and Δm denotes the difference between K_L and K_S mass. The four Δa_μ parameters are measure of the Lorentz symmetry violation. Neglecting higher order contributions to CP violation the two η parameters can be written as:

$$\begin{aligned} \eta_1 &\cong \epsilon_K - \delta_K(\vec{p_1}, t_s) \\ \eta_2 &\cong \epsilon_K - \delta_K(\vec{p_2}, t_s) \end{aligned} \tag{4}$$

Since the Earth is rotating the CPT and Lorentz violating parameters are usually considered in the fixed stars reference frame which makes δ_K dependent also on the sidereal time t_s after the

transformation from the laboratory frame [15].
At KLOE search for the Lorentz and CPT symmetries violation have been performed by measurements of the interference pattern for both kaons decaying to $\pi^+\pi^-$ final states. A sample of 1.7 fb^{-1} of integrated luminosity gathered in the 2004-2005 data taking period have been used in this analysis. Moreover, we have generate two Monte Carlo samples, one containing all the ϕ meson decay channels (used for analysis optimization) and an MC signal events sample which have been used for efficiency and decay time difference resolution determination. The first preselection of data was done requiring two vertices with two tracks of opposite curvature. Assuming the pion hypothesis for every track we have then applied a set of kinematical cuts [11]:

- $|m_{\mathrm{trk}} - m_{\mathrm{K}}| < 5$ MeV/c^2, where m_{K} denotes the kaon mass and m_{trk} is the invariant mass of the kaon reconstructed from the tracks assuming charged pion mass hypothesis: $\vec{p}_{1,2} = \vec{p}_{\pi^+} + \vec{p}_{\pi^-}$ and $E_{1,2} = E_{\pi^+} + E_{\pi^-}$.
- $\sqrt{E^2_{\mathrm{miss}} + |\vec{p}_{\mathrm{miss}}|^2} < 10$ MeV, where $\vec{p}_{\mathrm{miss}} = \vec{p_\phi} - \vec{p}_{2,1} - \vec{p}_{1,2}$ and $E_{\mathrm{miss}} = E_\phi - E_{2,1} - E_{1,2}$;
- -50 MeV ^{2}/c^4 $< m^2_{\mathrm{miss}} < 10$ MeV^2/c^4, where $m^2_{\mathrm{miss}} = E^2_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|^2$
- $|p^*_{1,2} - p^*_0| < 10$ MeV/c, where $p^*_{1,2}$ is the momentum of the kaon, as derived from tracks, in the ϕ meson reference frame, while $p^*_0 = \sqrt{s/4 - m^2_{\mathrm{K}}}$ and $\sqrt{s}$ is the center-of-mass energy.

On the basis of MC simulations the remaining data sample contain a small fraction of irreducible background mainly due to kaon regeneration on the thin beryllium cylindrical foil inside the interaction region ($\sim 2\%$) and due to the $e^+e^- \to 4\pi$ reaction. In order to improve the accuracy of decay time measurements a dedicated global fit procedure has been performed [11]. Since the resolution of decay time difference deteriorates at large pion opening angles $\theta_\pi$we have rejected all events with $\cos\theta_\pi < 0.975$.
The data sample was divided into two subsets in which the kaons going in the forward direction are emitted in a quadrant along with the ϕ momentum or opposite to its direction, and in the four bins of sidereal time. For every subset of data the decay intensity distribution as a function of Δt was determined. The distributions were fitted simultaneously with the interference pattern taken according to Eq. 2 and assuming possible modulation effects induced by the CPT-violating parameter δ_K as in Eq. 3. The resulting eight distributions are presented in Fig. 1, where the difference of decay times Δt is expressed in the units of K_S lifetime. The colored bands represent the fit uncertainty due to finite MC simulation statistics and efficiency correction.
The values of Δa_μ parameters determined from the fit amount to:

$$\begin{aligned}
\Delta a_0 &= (-6.0 \pm 7.7_{stat} \pm 3.1_{syst}) \times 10^{-18} \text{ GeV},\\
\Delta a_x &= (\ \ 0.9 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-18} \text{ GeV},\\
\Delta a_y &= (-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18} \text{ GeV},\\
\Delta a_z &= (\ \ 3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18} \text{ GeV}.
\end{aligned}$$

These results do not reveal any CPT or Lorentz symmetries violation and constitute the first estimation in the kaon sector. The detailed description of the systematic uncertainties can be foud in [11].

3. Future prospects
The CPT and Lorentz symmetries violation are one of the main physics topics of the KLOE-2 experiment which is continuing and extending the physics program of its predecessor [16]. For the forthcoming run the KLOE performance have been improved by adding new subdetector systems: the tagger system for the $\gamma\gamma$ physics, the Inner Tracker based on the Cylindrical GEM technology and two calorimeters in the final focusing region [17]. The new inner detector will increase the tracking and vertexing capabilities of KLOE allowing for significant reduction of systematic uncertainties which together with statistics expected to be gathered by KLOE-2 will significantly improve the present result.

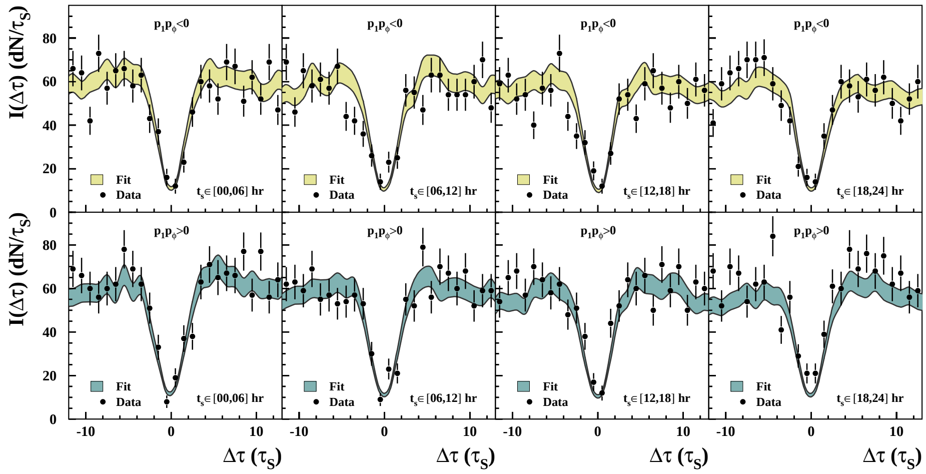

Figure 1. Distributions of the double differential decay rates into $\pi^+\pi^-, \pi^+\pi^-$ final states obtained for all the subsets of data.The top and bottom plots refer to the two angular selections. The results of the fit is indicated together with uncertainties by colored bands (figure taken from [11].)

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