STATUS AND PROSPECTS FOR LORENTZ AND CPT VIOLATION TESTS AT KLOE AND KLOE-2

ANTONIO DE SANTIS
Dipartimento di Fisica, Università di Roma ‘La Sapienza’
and I.N.F.N. Sezione di Roma
P.le A. Moro, 2
00185 Rome, Italy
E-mail: antonio.desantis@roma1.infn.it

on behalf of the KLOE/KLOE-2 collaborations

Abstract. The neutral kaon system offers a unique possibility to perform fundamental tests of CPT invariance. In this contribution the KLOE prospects for the measurements of CPT violation in the context of the Standard-Model Extension are presented. Preliminary results on the CPT violating parameters already obtained by KLOE analyzing only half of the available data with a simplified analysis scheme will be reported: $\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18}$ GeV, $\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18}$ GeV, $\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18}$ GeV. In this contribution we will discuss a new analysis method that will allow to measure the complete set of four parameters ($\Delta a_\mu$) also with the perspective given by the KLOE-2 data-taking campaign.

1. The KLOE experiment
The KLOE experiment operates at DAΦNE, the Frascati φ-factory. DAΦNE is an $e^+e^-$ collider running at a center of mass energy of $\sim 1020$ MeV, the mass of the φ meson. Positron and electron beams collide at an angle of $\pi-25$ mrad, producing $\phi$ mesons with small boost in the orbit plane ($p_x(\phi) \sim -15$ MeV).

The KLOE detector consists of a large cylindrical drift chamber (DC) surrounded by a lead-scintillating fiber electromagnetic calorimeter (EMC). A superconducting coil around the EMC provides a 0.52 T axial field. The DC[1] is 4 m in diameter and 3.3 m long and has 12,582 all-stereo tungsten sense wires. The chamber shell is made of carbon fiber-epoxy composite and the gas used is a 90% helium, 10% isobutane mixture. These features maximize transparency to photons and reduce $K_L \to K_S$ regeneration and multiple scattering. The position resolutions are $\sigma_r, \phi \sim 150$ µm and $\sigma_z \sim 2$ mm. The momentum resolution is $\sigma(p_\perp)/p_\perp \sim 0.4\%$. The calorimeter[2] is divided into a barrel and two end-caps, and covers 98% of the solid angle. The modules are read-out at both ends by photo-multipliers, both in amplitude and time for a total of 2440 cells per side arranged in five layers. Cells close in time and space are grouped into calorimeter clusters. The cluster energy $E$ is the sum of the cell energies. The cluster time $T$ and position $\bar{R}$ are energy-weighed averages. Energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$ and $\sigma_t = 57\text{ps}/\sqrt{E(\text{GeV})} \oplus 100\text{ ps}$, respectively.

At present KLOE has already acquired 2.5 fb$^{-1}$ of data and a new extensive campaign of data taking is starting aiming at an integrated luminosity of 25 fb$^{-1}$.
The production cross section for the process $e^+e^-\rightarrow\phi$ is $3.3\ \mu$b and the $\phi$ meson decays into $K_0\bar{K}_0$ with a branching fraction of $\sim34\%$. The initial state of the kaon pair is produced via strong interaction with quantum numbers $J^{PC}=1^{--}$:

$$|i\rangle = \frac{|K_0\rangle|\bar{K}_0\rangle - |\bar{K}_0\rangle|K_0\rangle}{\sqrt{2}} = \mathcal{N}(|K_S\rangle|K_L\rangle - |K_S\rangle|K_L\rangle),$$  \hspace{1cm} (1)$$

where $|K_S/K_L\rangle$ are the kaon mass eigenstate and $\mathcal{N}$ is a normalization factor. The two kaons are produced in an antisymmetric correlated state. The time evolution of the system that decay in the pair of final states $f_1$ and $f_2$ can be expressed as a function of the difference of decay time ($\Delta t = t_2 - t_1$) as:

$$I_{f_1,f_2}(\Delta t) \propto e^{-\Gamma|\Delta t|} \left[ |\eta_1|^2 e^{\frac{i\Delta m}{2} \Delta t} + |\eta_2|^2 e^{\frac{i\Delta m}{2} \Delta t} - 2\Re\left(\eta_1\eta_2 e^{-i\Delta m \Delta t}\right) \right]$$  \hspace{1cm} (2)$$

where $\eta_j = \langle f_j|K_L\rangle/\langle f_j|K_S\rangle, \ \Gamma = \Gamma_S + \Gamma_L$ and $\Delta \Gamma = \Gamma_S - \Gamma_L$.

---

**Figure 1.** Left: distribution of eq. 2 for $f_1 = f_2 = f$. Right: description of the sidereal reference frame and relative coordinate transformation.

If the final states considered are the same for the two kaons ($f_1 = f_2 = f$) it is not possible to distinguish between them. In the standard Quantum Mechanics description of the time evolution of the system, a fully destructive interference is expected for equal decay time ($|\Delta t| = 0$) as shown if fig. 1(left). In the case $f = \pi^+\pi^-$ we have $\eta_f = \eta_+ \simeq \varepsilon_K - \delta_K$, where $\varepsilon_K$ and $\delta_K$ are the $CP$ and $CPT$ violation parameters in the mixing, respectively (violations in the decay have been neglected being irrelevant here). In the following we will use the notation $I_{\pm}(\Delta t) = I_{f_1,f_2}(\Delta t)$ with $f_1 = f_2 = \pi^+\pi^-$.

2. **CPT and Lorentz symmetry breaking**

A general theoretical possibility for $CPT$ violation is based on spontaneous breaking of Lorentz symmetry, as developed by Kostelecky[3, 4, 5]: the Standard-Model Extension (SME). Following this theoretical approach, for neutral kaons, $CPT$ violation manifests to lowest order only in
the parameter $\delta_K$ and is related to Lorentz Invariance breaking. This results in a dependence of $\delta_K$ on the 4-momentum of the kaon:

$$\delta_K \approx i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K (\Delta a_0 - \tilde{\beta}_K \cdot \Delta \vec{a}) / \Delta m,$$

where $\gamma_K$ and $\tilde{\beta}_K$ are the kaon boost factor and velocity in the observer frame, and $\Delta a_\mu$ are the CPT violation coefficients for the two valence quarks in the kaon.

The simple expression in (3) holds if the observer reference frame is at rest with respect to fixed stars (sidereal reference frame). To take into account that our laboratory on the Earth is moving we have to consider a coordinates transformation. The rotation of the Earth will results in a dependence of the $\delta_K$ parameter on the sidereal time. Choosing a three-dimensional basis $(\hat{X}, \hat{Y}, \hat{Z})$ in a non-rotating frame, with the $\hat{Z}$ axis along the Earth’s rotation axis, and a basis ($\hat{x}, \hat{y}, \hat{z}$) for the laboratory frame[4] (see fig. 1) eq. 3 will transform as:

$$\delta_K(\vec{p}_K, t) = \frac{i \sin \phi_{SW} e^{i \phi_{SW}}}{\Delta m} \gamma_K \left[ \Delta a_0 + \beta_K \Delta a_Z (\cos \vartheta \cos \chi - \sin \vartheta \cos \phi \sin \chi) - \beta_K \Delta a_Y \sin \vartheta \sin \phi \sin \Omega T + \beta_K \Delta a_X (\cos \vartheta \sin \chi + \sin \vartheta \cos \phi \sin \chi) \cos \Omega T + \beta_K \Delta a_Y (\cos \vartheta \sin \chi + \sin \vartheta \cos \phi \sin \chi) \sin \Omega T - \beta_K \Delta a_Y \sin \vartheta \sin \phi \cos \Omega T \right],$$

where $T$ is the sidereal time, $\Omega$ is the Earth’s sidereal frequency and $\chi$ is the angle between the Earth rotation axis and the $\hat{z}$ direction in the laboratory frame; $\vartheta$ and $\phi$ are the polar and azimuthal angles in the laboratory frame.

Every $\Delta a_\mu$ component in eq. 4 has his own dependence with respect to sidereal time and kaon flight direction. This kind of dependence will be exploited in our analysis of the KLOE data to access the complete set of SME parameters.

3. KLOE approach

Using KLOE data, it is possible to perform different analysis to determine the SME parameters for the kaon system, extensively discussed in Ref. [6]. In this contribution we will discuss the possibility offered by kaon interferometry when using the same final state, i.e. $f_1 = f_2 = \pi^+ - \pi^-$.

In KLOE the two kaons decay with opposite momenta thus experiencing, on a event by event basis, two different modulation for the $\delta_K$ parameter appearing in $\eta_\pm$ coefficients as described in eq. 3.

Ordering the two decay times according to the kaon direction in the lab frame, it is possible to construct the decay amplitude in eq. 2 directly as function of $\Delta t$ even in this case in which is not possible to distinguish the two decays. Because of eq. 4 we expect small asymmetries in the two branches of the function ($\Delta t < 0$ vs $\Delta t > 0$) that should exhibit the expected modulation as a function of sidereal time and kaon directions. This will allow to define the following quantity:

$$A(\Delta t) = \frac{I_+(\Delta t > 0) - I_-(\Delta t < 0)}{I_+(\Delta t > 0) + I_-(\Delta t < 0)}.$$  

The above asymmetry for $\Delta t \gg \tau_S$ tends to zero, because $\varepsilon_K$ and $\delta_K$ are $90^\circ$ out of phase [7]:

$$A(\Delta t \gg \tau_S) \simeq -2Re \left( \frac{\delta_K}{\varepsilon_K} \right) \sim 0,$$

1 Two kaons are not produced exactly back to back because of the $\phi$ boost in the lab frame. This small effect will be fundamental to access all the four $\Delta a_\mu$ parameters as discussed in the text.
while for $|\Delta t| \leq 5\tau_S$

$$A(|\Delta t| < 5\tau_S) \propto -23m \left( \frac{\delta K}{\tau_K} \right).$$

Eq. 7 implies that one of the most critical point in the analysis will be the resolution on the difference of decay times. To improve as much as possible on this respect we have to apply severe selection criteria to guarantee the high quality and low contamination of the gathered dataset. At the end of the selection chain the background contamination in the sample is of the order of 1.7% and is mainly due to the kaon regeneration on the beam pipe.

Since the signal has a very clean topology, two decay vertex reconstructed from two pairs of tracks, we exploit the possibility to use global event information in the signal hypothesis to improve the reconstruction. This is done by performing a global fit of the event to redetermine the decay length of the two kaons leaving free the position of the primary vertex. In the standard reconstruction the position of the primary vertex is determined by using a special sample of bhabha events for the whole run. This method will provide, for a standard run, a resolution of the order of centimeters, while the global fit can provide results up to few millimeters, as shown in fig. 2-left.

![Figure 2](image.png)

**Figure 2.** Left: Resolution on the proper decay time difference. The black is the output of the standard reconstruction, the red one is the output of the global fit. The events are the same in both cases. Right: pictorial description of the methods used in the preliminary analysis (top) and current approach (bottom). The red arrow represents the $\phi$ boost.

With KLOE data we already performed a preliminary analysis [8] using only half of the total available statistics (1 fb$^{-1}$). In this analysis we used the forward-backward asymmetry along $z$ direction as a function of sidereal time only (e.g. integrating over azimuthal angle see fig. 2-right). With this approach only the vector part of the $\Delta a_{\mu}$ four-vector can be observed$^2$. Our preliminary results on $\Delta a_{X,Y,Z}$ are:

$$\Delta a_X = (-6.3 \pm 6.0) \times 10^{-18} \text{ GeV},$$

$^2$ The integration over azimuthal angle does not allow to make observations as a function of the kaon momenta value (e.g. $\gamma_K$). According to eq. 4 this will wash out the $\Delta a_0$ contribution to the asymmetry.
\[
\Delta a_Y = (2.8 \pm 5.9) \times 10^{-18} \text{ GeV}, \\
\Delta a_Z = (2.4 \pm 9.7) \times 10^{-18} \text{ GeV}. \tag{8}
\]

The \( \Delta a_0 \) parameter is coupled only with the \( \gamma_K \) factor without any sidereal or spatial modulation, as shown in eq. 3. Since at DA\( \Phi \)NE the \( \phi \) is produced with a small boost in the horizontal plane the kaons have different values for \( \gamma_K \) as a function of the azimuthal angle. This will make possible a different approach with respect to the one used for the preliminary results. The kaons can be ordered according to their \( z \) component of the momentum, as in the previous case (forward-backward). Then we can split the event sample according to the sign of the \( x \) component for the kaon going in the forward direction. As shown in fig. 2-right, this choice corresponds to divide the data sample in two subset for which the kaons going in the forward direction has higher (lower) value for \( \gamma_K \) since it is emitted along (opposite) to the \( \phi \) boost. In this way we can enhance the effect of the SME parameter \( \Delta a_0 \), as shown in fig. 3-left. In the plots a simulation with all parameters but \( \Delta a_0 \) set to zero is shown. For values of \( \Delta a_0 \) of the order \( O(10^{-18}) \) GeV we expect an effect on the \( I_{\pm}(\Delta t) \) up to 1%-2% in the region \( |\Delta t| < 5 \tau_S \) from which we expect to be able to put limits of the order \( O(10^{-17})-O(10^{-18}) \) GeV.

The \( \Delta a_\mu \) parameters can be all simultaneously measured by performing a proper sidereal time dependent analysis of asymmetries of \( I_{\pm}(\Delta t) \), eq. 2 and eq. 4. An accuracy \( O(10^{-18}) \) GeV could be reached with the analysis of the full KLOE data sample.

![Figure 3](image_url)

**Figure 3.** Left: effect of \( \Delta a_0 \) parameters on the decay rate distribution. Red and blue in the top plot refers to the different pair of sectors chosen, while bottom plot is the ratio between the two. Right: effect on the resolution with the upgrades proposed for KLOE-2.

4. Conclusions and future plans

All four \( \Delta a_\mu \) parameters of the SME can be independently measured at KLOE, completing results obtained by fixed beam experiments.

The continuation of the KLOE physics program with KLOE-2 [9] at an improved DA\( \Phi \)NE machine is currently starting. The data taking campaign will be organized in two different steps. During the first one we will double the statistics already taken by KLOE with a new
beam interaction scheme [10] and with the inclusion of two pairs of electron-positron taggers [11] for the study of the gamma-gamma physics. In this first phase we will benefit of the increased statistics and also we can expect improvements due to the new interaction region geometry both for regeneration, because the interior part of the beam pipe has been redesigned, and for the increased crossing angle, that will results in a increased range for $\gamma K$ coefficient.

The second phase aims to an integrated luminosity of $\sim 25 \text{ fb}^{-1}$ including several upgrades for the KLOE detector:

- a pair of crystal calorimeters (CCALT[12]) near the interaction region to improve the angular acceptance for low-$\theta$ particles;
- a pair of tile calorimeters (QCALT[13]) covering the quadrupoles along the beam pipe made of tungsten foil and singly read-out scintillator tiles to improve the angular coverage for particles coming from the active volume of the DC;
- a small and light tracker (IT[14]) made of four planes of cylindrical GEM to improve the resolution of the vertex reconstruction around the interaction point and to increase the low-$\vartheta$ charged particles acceptance.

In this second phase we expect an improvement of the decay vertex resolution, because of the Inner Tracker. As shown in fig. 3, we should obtain an increase in the resolution of $\Delta t$ of a factor of three/four. This, together with the increased statistics, should allow us to improve the results on CPT violation parameters by more than one order of magnitude.

References
[1] M. Adinolfi et al., KLOE Collaboration, Nucl. Inst. Meth. A 488 (2002) 51.
[2] M. Adinolfi et al., KLOE Collaboration Nucl. Inst. Meth. A 482 (2002) 363.
[3] V.A. Kostelecký, Phys. Rev. Lett. 80, 1818 (1998).
[4] V.A. Kostelecký, Phys. Rev. D 61, 016002 (1999).
[5] V.A. Kostelecký, Phys. Rev. D 64, 076001 (2001).
[6] A. Di Domenico, in V.A. Kostelecký, ed., Fourth Meeting on CPT and Lorentz Symmetry, World Scientific, Singapore, 2008; A. Di Domenico, in A. Di Domenico ed., Handbook on neutral kaon interferometry at a $\Phi$-factory, Frascati Physics Series, Vol. 43.
[7] C. D. Buchanan et al., Phys. Rev. D 45, 4088 (1992).
[8] A. Di Domenico, J. Phys. Conf. Ser. 171, 012008 (2009).
[9] G. Amelino-Camelia et al., arXiv:1003.3868.
[10] C. Milardi et al., DAFNE Collaboration, arXiv:1006.1487.
[11] D. Babusci et al., Nucl. Instrum. Meth. A 617, 81 (2010).
[12] F. Happacher et al., Nucl. Phys. Proc. Suppl. 197, 215 (2009).
[13] M. Cordelli et al., Nucl. Instrum. Meth. A 617, 105 (2010).
[14] F. Archilli et al., KLOE-2 Collaboration, arXiv:1002.2572.