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Study of CP and CPT symmetries violation in Kaon decays with KLOE

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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 ϕ-meson decays offers 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 to independently measure all four CPT violating parameters Δa_μ for kaons in the SME. The final results of the analysis on Δa_μ are:

$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{syst}) \times 10^{-18}$ GeV,
$\Delta a_X = (\ 0.9 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-18}$ GeV,
$\Delta a_Y = (-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18}$ GeV,
$\Delta a_Z = (\ 3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18}$ GeV.

The $K_S \to \pi^0\pi^0\pi^0$ decay is a pure CP violating process which, assuming CPT invariance, allows direct CP violation to be investigated. This decay has not been observed so far. The new best upper limit $BR(K_S \to \pi^0\pi^0\pi^0) < 2.6 \times 10^{-8}$ at 90% C.L. has been set with the KLOE detector. This result improved by a factor of five the previous limit and is one order of magnitude larger than the Standard Model prediction.

Perspectives on these measurements using the KLOE-2 apparatus upgraded with an Inner Tracker and low-theta angle calorimeters will be discussed.

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1. The KLOE experiment

The KLOE experiment has collected 2.5 fb^{-1} of integrated luminosity at DAΦNE the e^+e^- Φ-factory at the INFN Laboratori Nazionali di Frascati, fulfilling a vast program of precision kaon and hadron physics measurements [1]. With its general purpose detector, consisting of a large cylindrical drift chamber surrounded by a lead-scintillating fiber electromagnetic calorimeter entirely immersed in an axial magnetic field, KLOE produced the most comprehensive set of results on kaon physics from a single experiment using the unique availability of pure K_S ,K_L and $K^{\pm}$ beams at a ϕ–factory .

2. CPT and Lorentz Symmetry: $\phi \to K_S K_L \to \pi^+\pi^-, \pi^+\pi^-$

At DAΦNE the ϕ -meson is produced almost at rest and decays mostly in kaon pairs: 34% of decays are neutral kaons. The initial state of the kaon pair produced with $J^{PC} = 1^{--}$ quantum numbers is: $|i\rangle = (|K_0\rangle|\overline{K}_0\rangle - |\overline{K}_0\rangle|K_0\rangle)/\sqrt{2} = \mathscr{N}(|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_S(-\vec{p})\rangle|K_L(\vec{p})\rangle)$, with $|K_S/K_L\rangle$ the kaon mass eigenstates and $\mathscr{N}$ a normalization factor. The neutral kaon mass eigenstates can be written as:

$$\begin{cases} |K_S\rangle = [(1+\varepsilon_S)|K_0\rangle + (1-\varepsilon_S)|\overline{K}_0\rangle]/N_S \\ |K_L\rangle = [(1+\varepsilon_L)|K_0\rangle - (1-\varepsilon_L)|\overline{K}_0\rangle]/N_L \end{cases} \tag{2.1}$$

with $\varepsilon_{S/L} = \varepsilon_K \pm \delta_K$ where ε_K is the CP violation parameter in the neutral kaon mixing and δ_K is the CPT violation parameter. Assuming no CPT violation $\varepsilon_S = \varepsilon_L$.

The time evolution of the initial state $|i\rangle$ decaying into $|f_1, f_2\rangle$ final state can expressed as a function of the proper decay time difference $\Delta\tau = \tau_2 - \tau_1$:

$$I_{f_1 f_2}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\left[|\eta_{f_1}|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_{f_2}|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re e\left(\eta_{f_1}\eta^*_{f_2} e^{-i\Delta m\Delta\tau}\right)\right] \tag{2.2}$$

with $\eta_{f_j} = \langle f_j|K_L\rangle / \langle f_j|K_S\rangle$, $\Gamma = \Gamma_S + \Gamma_L$, $\Delta\Gamma = \Gamma_S - \Gamma_L$, showing the time interference term correlating the f_1 and f_2 decays even if the kaons are distant in space. Moreover complete destructive quantum interference prevents the two kaons from decaying into the same final state $f_1 = f_2 = f$ at the same time $|\Delta\tau| = 0$. Assuming $f_j = \pi^+\pi^-$ the resulting ratio of amplitudes becomes $\eta_j = \eta_{\pi^+\pi^-} \simeq \varepsilon_K + \varepsilon' - \delta_K$.
According to the Standard Model Extension (SME) [2] CPT violation should appear together with Lorentz Invariance breaking thus implying a direction dependent modulation. In this SME framework the δ_K parameter is expected to be modulated by kaon momentum and direction:

$$\delta_K \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a})/\Delta m, \tag{2.3}$$

with γ_K and β_K the kaon Lorentz factors, ϕ_{SW} the super-weak phase and Δa_μ the SME parameters for the kaon system. At KLOE the two kaons are produced almost back-to-back, due to the ϕ-meson momentum, and therefore evolve with two different δ_K parameters ($\delta_K(\vec{P}_1) \neq \delta_K(\vec{P}_2)$). The effect produced by CPT violation can be observed in the distribution of equation 2.2 provided the two kaon final states are tagged with respect to some privileged reference frame.

Accounting for the Earth motion with respect to fixed stars, the CPT violation parameter becomes:

$$\begin{aligned}\delta_K(\vec{P}_K, T_{sid}) = & \frac{i \sin\phi_{SW} e^{i\phi_{SW}}}{\Delta m}\gamma_K \Big[\Delta a_0 + \beta_K \Delta a_Z(\cos\vartheta\cos\chi - \sin\vartheta\cos\varphi\sin\chi) \\ & -\beta_K \Delta a_X \sin\vartheta\sin\varphi\sin\omega_E T_{sid} \\ & +\beta_K \Delta a_X(\cos\vartheta\sin\chi + \sin\vartheta\cos\varphi\cos\chi)\cos\omega_E T_{sid} \\ & +\beta_K \Delta a_Y(\cos\vartheta\sin\chi + \sin\vartheta\cos\varphi\cos\chi)\sin\omega_E T_{sid} \\ & +\beta_K \Delta a_Y \sin\vartheta\sin\varphi\cos\omega_E T_{sid}\Big] \qquad (2.4)\end{aligned}$$

with ω_E the Earth angular velocity, T_{sid} the sidereal time, χ the angle between the axis of the laboratory frame $\hat{z}_{LAB}$ and the Earth rotation axis and ϑ and φ are the polar and azimuthal angle in the laboratory, respectively. The Δa_X and Δa_Y parameters are sensitive to the sidereal time dependence of δ_K. The Δa_0 parameter, coupled to γ_K only, will be the most difficult to observe, considering the 2-3% variation of γ_K at KLOE.

Using equation 2.4 in the time evolution of the kaon system and ordering the two kaons according to the P_z component of their momentum, gives:

$$\begin{aligned}I(\Delta t, T_{sid}, \vartheta_{K_1}, \varphi_{K_1}) \propto\ & e^{-\Gamma|\Delta\tau|}\Big[|\varepsilon_K - \delta_K(\vec{P}_1)|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + \\ & |\varepsilon_K - \delta_K(\vec{P}_\phi - \vec{P}_1)|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - \qquad (2.5) \\ & 2\Re e\Big((\varepsilon_K - \delta_K(\vec{P}_1)(\varepsilon_K - \delta_K(\vec{P}_\phi - \vec{P}_1))^* e^{-i\Delta m\Delta\tau}\Big)\Big]\end{aligned}$$

with $\vartheta_{K_1}, \varphi_{K_1}$ the polar and azimuthal angle of the first kaon. The ϕ-meson momentum and the angular distribution of kaon decays, allowing almost all the direction in space to be explored, are the key to accurate measurements of all the Δa_μparameters at KLOE.

In order to measures Δa_μ parameters, 1.7 fb^{-1} of the KLOE data-set have been analized as a function of sidereal time and kaon direction. The signal selection, extensively described in Ref.[3], requires two vertices with two tracks and kinematical cuts are applied to reduce background contamination. Then a global fit is performed to improve the resolution on the decay time difference.

To enhance the sensitivity to the Δa_0 parameter, the data sample has been divided according to kaon direction with respect to ϕ-meson momentum (e.g. $P_x > 0$ or $P_x < 0$) and the observable has been defined as:

$$S(\Delta\tau_i, \Delta T_{sid\,j}, \Delta\Omega_h) = S_{ijh} = \int_{\Delta\tau_i} d\Delta\tau \int_{\Delta T_{sid\,j}} dT_{sid} \int_{\Delta\Omega_h} d\Omega_{K_1}\rho(\Omega_{K_1}, T_{sid})\, I(\Delta\tau, T_{sid}, \Omega_{K_1}) \qquad (2.6)$$

with $\rho(\Omega_{K_1}, T_{sid})$ the angular and sidereal time density distribution for the first kaon K_1, produced with $P_z > 0$. The number of different $\Delta\tau$ distributions used for the measurements is eight: 4 sidereal time bins × the two angular bins $\cos\vartheta_{K_1} > 0 \cos\varphi_{K_1} > 0$ (sel. "I-III") and $\cos\vartheta_{K_1} > 0 \cos\varphi_{K_1} < 0$ (sel. "II-IV"). The range $\Delta\tau \in [-12:12]\tau_S$, has been chosen to limit the effect of regeneration on the spherical beam pipe. To fit the data distributions, efficiency and resolution corrections have been applied to the theoretical expression of equation 2.6. To this purpose dedicated Monte Carlo simulations and data control samples have been used.

The final results on Δa_μ parameters, obtained from the simultanoeus fit of the eight data distributions, are reported in table 1. The total uncertainty is statistically dominated.

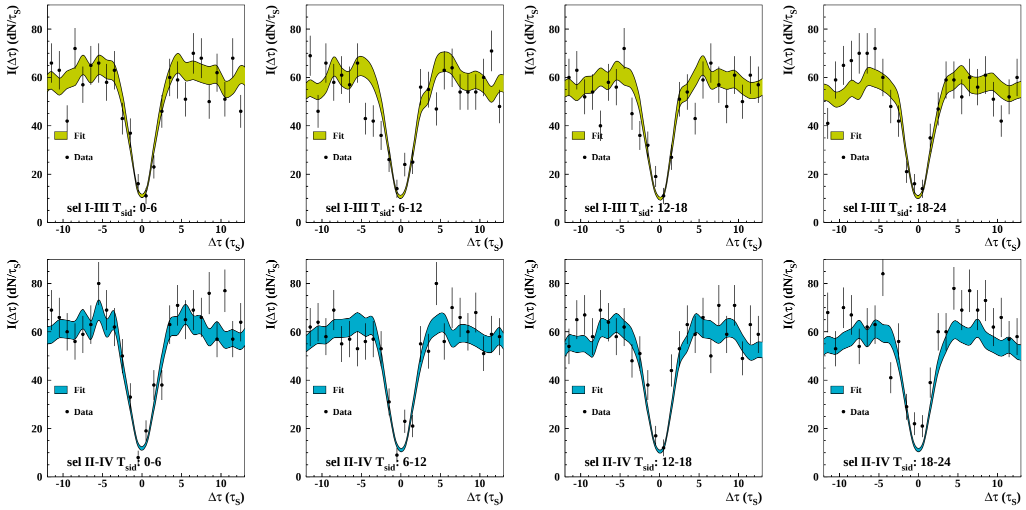

Figure 1: Fit results: Top (Bottom) plots are for the angular selection "I-III"("II-IV") . Black points are data and colored bands are the fit output. The errors on data are statistical only, while the fit result band includes uncertainty from Monte Carlo statistics and efficiency correction.

Table 1: Fit results. Errors include the statistical fluctuations and are in the expected range. The fit χ^2/ndf is 211.7/184 corresponding to a p-value of 8%.

Par.	Fit output (10^{-18} GeV)	Correlation matrix			
		Δa_0	Δa_X	Δa_Y	Δa_Z
Δa_0	$(-6.0 \pm 7.7_{stat} \pm 3.1_{syst})$	1.000	0.304	-0.187	0.483
Δa_X	$(\ \ 0.9 \pm 1.5_{stat} \pm 0.6_{syst})$	0.304	1.000	-0.045	0.069
Δa_Y	$(-2.0 \pm 1.5_{stat} \pm 0.5_{syst})$	-0.187	-0.045	1.000	-0.104
Δa_Z	$(\ \ 3.1 \pm 1.7_{stat} \pm 0.6_{syst})$	0.483	0.069	-0.104	1.000

3. *CP* Symmetry: $K_S \to \pi^0\pi^0\pi^0$

The $K_S \to 3\,\pi^0$ decay is a pure *CP* violating process. The related *CP* violation parameter is defined as the ratio of K_S to K_L decay amplitudes $\eta_{000} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0) = \varepsilon_S + \varepsilon'_{000}$ with $\varepsilon_S = \varepsilon + \delta$ related to the K_S *CP* impurity and ε'_{000} to direct *CP* violation. In Chiral Pertubation Theory at the lowest order $\varepsilon'_{000} = -2\varepsilon'$ [4, 5], with ε' the direct *CP* violation parameter in $\pi\pi$ decays. Thus $\eta_{000} \simeq \varepsilon_S$ and BR($K_S \to 3\pi^0$) $\simeq 1.9 \times 10^{-9}$ to an accuracy of a few %, in the Standard Model and assuming *CPT* invariance $\varepsilon_S = \varepsilon$. Therefore the direct observation of this decay would unambiguously sign *CP* violation in the mixing and/or in the decay. The previous best upper limit on BR($K_S \to 3\pi^0$) was obtained with the KLOE experiment using 450 pb^{-1} integrated luminosity, exploting the unique feature of a K_S beam available at a ϕ-factory and provided by events tagged by K_L interactions in the EMC, hereafter K_L-crash [6]. This limit has been updated using the entire 1.7 fb^{-1} KLOE data set and improving the K_S tagging algorithm hardening the

$\beta^*(K_L)$ cut for the K_L -crash identification [7]. The signal selection requires six neutral clusters coming from the IP. The main background originates from the $K_S \to 2\pi^0$ events with two spurious clusters from fragmentation of the electromagnetic showers, hereafter splitting, or accidental activity. The analysis performed on the entire KLOE data set has improved the clustering procedure to reject splitting. A second source of background comes from fake K_L -crash identification from $\phi \to K_S K_L \to \pi^+\pi^-, 3\pi^0$ events. In these events, charged pions from K_S decays interact in the DAΦNE low-β intersection quadrupoles simulating the K_L interaction in the calorimeter, and K_L decays close to the IP produce the six photons required from the signal selection. This background is suppressed rejecting events with charged particles coming from the vicinity of the IP, and then cutting on the reconstructed velocity and energy of the tagging K_L .

A kinematic fit with 11 constraints is performed with energy and momentum conservation, the kaon mass and the velocity of the six photons. In order to reject events with cluster splittings and accidentals, the correlations between two χ^2-like discriminating variables, $\chi^2_{3\pi}$ and $\chi^2_{2\pi}$, is used. The $\chi^2_{3\pi}$ variable verifies the signal hypothesis by looking at the reconstructed masses of three pions. The $\chi^2_{2\pi}$ variable is calculated selecting four out of the six clusters providing the best kinematic agreement with the $K_S \to \pi^0\pi^0 \to 4\gamma$ hypothesis. The pairing of the clusters is based on the requirement $m_{\gamma\gamma} = m_{\pi^0}$, and on the opening angle of the reconstructed pions trajectories in the K_S center of mass frame. To improve the quality of the photon selection we cut on $\Delta E = M_\phi/2 - \sum E_{\gamma_i}/\sigma_E$ summing over the four photons chosen to calculate $\chi^2_{2\pi}$, and σ_E is the energy resolution. For signal events the missing π^0 implies $\Delta E \sim M_{\pi^0}/\sigma_E$. To refine the rejection of events with split clusters, a cut on the minimal distance between photon clusters is applied. No events were found on data in the signal region and no background events were found in the simulated Monte Carlo sample with twice the data statistics. In the conservative assumption of no background, the upper limit $UL(N_{3\pi^0})$ = 2.3 at 90% C.L. on the expected signal events has been obtained. Correcting for the signal selection efficiency $\varepsilon_{3\pi^0} = 0.23 \pm 0.01$ and normalizing for $(1.142 \pm 0.005) \times 10^8$ $K_S \to \pi^0\pi^0$events found in the K_S tagged sample, the upper limit [6].

$$\mathrm{BR}(\mathrm{K_S} \to 3\pi^0) < 2.6 \times 10^{-8} \text{at 90\% C.L.}$$

has been set, almost five times lower than our previous result [6]. This limit can be directly translated in $|\eta_{000}| < 0.0088$ at 90% C.L. [6].

4. The upgraded apparatus: KLOE-2

KLOE-2 represents the continuation of KLOE, at an upgraded DAΦNE machine, with a new physics program mainly focused on K_S, η and η' rare decays as well as on kaon interferometry and search for physics beyond the Standard Model [8]. To study $\gamma\gamma$-physics, two pairs of electron-positron taggers have been installed: the Low Energy Tagger (LET) [9], inside the KLOE apparatus, and the High Energy Tagger (HET) [10] along the beam lines outside the KLOE detector. More recently the detector has been upgraded with: i) CCALT, a pair of crystal calorimeters positioned near the interaction region to improve the angular acceptance for low-θ photons [11], 2) QCALT, a pair of tile calorimeters [12], covering the quadrupoles inside the KLOE detector and along the beam pipe, to improve the angular coverage for particles coming from the active volume of the

Drift Chamber, iii) Inner Tracker, four layers of cylindrical triple-GEM-based detectors to improve the vertex reconstruction near the interaction point [13].

The $K_S \to \pi^0\pi^0\pi^0$ search at KLOE-2 will benefit from new low-theta calorimeters insertion, improving acceptance coverage and reducing backgrounds, and with the increased statistics the first observation of this decay at KLOE-2 seems feasible.

The sensitivity of CPT and Lorentz Invariance tests at KLOE-2 will improve both with the increased statistics and the IT insertion on the new interaction region (IR). The IT will improve the resolution on the vertex position and the new IR with a larger beam crossing angle (from 25 to 60 mrad) will enhance the effect of asymmetry between the two kaons and therefore the difference between $\delta_K(\vec{P}_1)$ and $\delta_K(\vec{P}_2)$. The expected sensitivity should increase up to 10^{-19} GeV for all the Δa_μ parameters.

5. Conclusions

The Kaon sector proves to be still a powerful tool to explore fundamental symmetries. The expected sensitivity of 10^{-18} GeV on Standard Model Extension parameters Δa_μ from Kaon sector has been reached exploting kaon interferometry. The new best upper limit on BR($K_S \to \pi^0\pi^0\pi^0$) and $|\eta_{000}|$ has been set.
KLOE-2 physics run is in preparation. New detectors have been integrated on DAΦNE beam-pipe. Both KLOE-2 and DAΦNE commissioning have then started.

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