

Recent KLOE results on Kaon Physics

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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 phi-meson decays offer unique possibilities 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 $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^-, \pi^+ \pi^0$ 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. We also shortly discuss the perspectives for a new measurement using the KLOE-2 apparatus equipped with a new inner tracker. The measurement of the absolute BR of the $K^+ \rightarrow 3\pi(\gamma)$ decay completes the KLOE program of precise and fully inclusive kaon dominant BR measurements. The most recent result, $\text{BR}(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = (5.56 \pm 0.20)\%$ (Chiang et al.), dates back to more than 30 years ago. We use a normalization sample of events tagged by $K \rightarrow \mu \nu$ and $K \rightarrow \pi \pi^0$ decays and require at least two reconstructed tracks (pion candidates). Finally the number of $K \rightarrow 3\pi(\gamma)$ decays is counted from the missing mass spectrum of the third pion to extract the branching ratio. The final KLOE result on the $\text{BR}(K^+ \rightarrow \pi^+ \pi^+ \pi^-(\gamma))$ is also presented.

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1. The KLOE experiment

KLOE (K Long Experiment) is located at one of the two interaction regions of the DAΦNE collider operating at the National Laboratory of Frascati, Italy. At DAΦNE electrons and positrons collide with $\sqrt{s} \approx 1020 \text{ MeV} = m_\phi$, producing predominantly ϕ mesons being almost at rest ($p_\phi \approx 12 \text{ MeV}/c$). The ϕ mesons decay into pairs of kaons, either neutral or charged, with branching ratios of 34% and 49%, respectively, allowing the KLOE detector which surrounds the decay point to study a broad range of kaons physics. Production of the kaons in pairs provides two unique features of the KLOE experiment, i.e. the possibility of tagging kaon states and quantum entanglement. The former means that detection of charged or neutral kaon guarantees the presence of its corresponding orthogonal state in the same event, which is used to obtain pure beams of charged or neutral kaons e.g. for branching ratio measurements. The second feature is the quantum coherence of the two kaon states which allows for measurements using quantum interferometry.

KLOE is a barrel-shaped detector composed mainly of a cylindrical drift chamber with a radius of 2m and a lead-scintillating fiber sampling electromagnetic calorimeter which surrounds the drift chamber covering 98% of full solid angle. While the size of detector was chosen so as to capture about 40% of the long-lived kaon decays, the K_S decays are contained within a spherically-shaped beam pipe with 10cm radius designed to avoid K_S regeneration on the BP material. The detector collected a total of about 2.5 fb^{-1} of data in two runs in the years 2001-2002 and 2004-2005, with loose trigger conditions which allow for a broad physics program.

2. CPT and Lorentz symmetry test with entangled neutral kaons

According to the Standard Model Extension (SME) [1] and the Anti-CPT theorem [2], CPT violation should appear together with breaking of Lorentz invariance. The SME parameters related to the kaon sector can be estimated using the methods of quantum interferometry. The amplitude of two entangled neutral kaons decaying into final states f_1 and f_2 in times differing by $\Delta\tau$ can be expressed as below:

$$I_{f_1 f_2}(\Delta\tau) = C e^{-\Gamma|\Delta\tau|} \left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re\left(\eta_1 \eta_2^* e^{-i\Delta m \Delta\tau}\right) \right], \quad (2.1)$$

where $\Delta\Gamma = \Gamma_S - \Gamma_L$, $\Gamma = (\Gamma_S + \Gamma_L)/2$, C is a normalization constant, $\eta_j = \frac{\langle f_j | T | K_L \rangle}{\langle f_j | T | K_S \rangle}$ and the last term in eq. 2.1 arises from quantum interference of kaon states. If both final states are chosen as $\pi^+ \pi^-$, η_1 and η_2 can be expressed in terms of the parameters ε_K and δ . In the framework of SME, however, δ is not constant and exhibits a modulation dependent on the direction of the kaon according to:

$$\delta \simeq i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta}_K \Delta \vec{a}) / \Delta m, \quad (2.2)$$

where ϕ_{SW} is the superweak phase, γ_K and $\vec{\beta}_K$ are the kinematic parameters of the corresponding kaon and Δa_0 , $\Delta \vec{a}$ are the coefficients violating CPT and Lorentz symmetries in the SME. The Δa_μ parameters may be extracted from a measurement of the δ parameter direction and energy dependence.

Since for the $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ process the two kaons travel with almost opposite momenta in the laboratory frame, their associated δ parameters should differ and the two relations:

$$\eta_1 = \varepsilon_K - \delta(\vec{p}_{K^1}), \quad \eta_2 = \varepsilon_K - \delta(\vec{p}_{K^2}), \quad (2.3)$$

lead to an effect on the distribution given in eq. 2.1. In order to observe it, the δ direction dependence is expressed in the reference frame of fixed stars, which also introduces its dependence on sidereal time.

The strategy of selection of $\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ events relies on a requirement of two reconstructed vertices with two associated tracks each and a set of cuts limiting the missing kinematic variables as the charged pion tracks provide full kinematic information on the signal events. Moreover, the considered time difference between kaon decays is limited to $\Delta\tau \in [-12\tau_S; 12\tau_S]$ in order to avoid K_L regeneration on the beam pipe material. The kaon decay length reconstruction is improved by means of a global kinematic fit. The residual contamination of the selected sample consists of kaon regeneration (2%) and direct $\phi \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decays (0.5%).

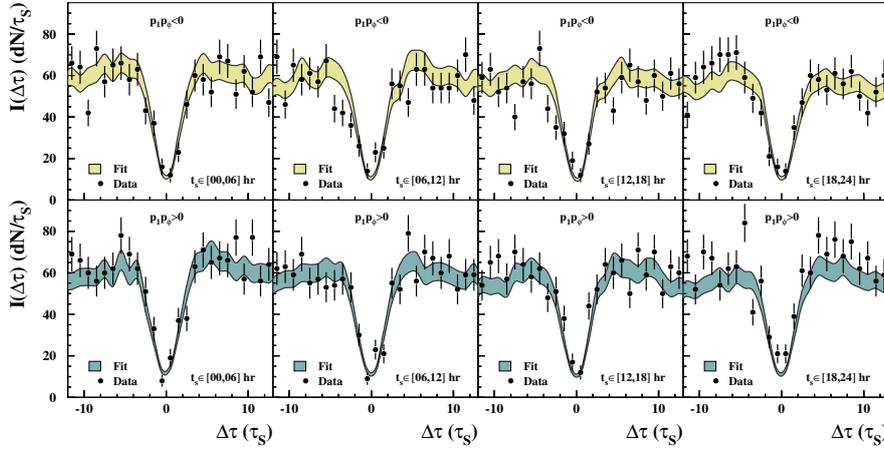


Figure 1: Results of the fit (color bands) to the double decay intensity distributions for data (black points) divided into 4 bins of sidereal time and two angular bins [3].

In order to observe the effect of direction-dependent modulation of δ on the intensity from eq. 2.1, the two kaons are ordered by the z -component of their momentum and the selected dataset is divided into two angular samples - one where a kaon with $\cos(\theta_{\vec{p}}) > 0$ in the detector frame has $\vec{p}_K \cdot \vec{p}_\phi > 0$ and one with $\vec{p}_K \cdot \vec{p}_\phi < 0$. The data is further divided into 4 samples of sidereal time ranges which results with 8 samples of data for which the decay amplitude distributions are simultaneously fit to extract the Δa_μ parameters. The result of the fit is shown in fig. 1. The obtained values of the SME parameters are the following:

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

Reaching the expected sensitivity at the level $O(10^{-18}\text{GeV})$, these results are presently the most precise measurements in the quark sector of the SME [3]. As the statistical uncertainties are dominating, there are prospects for improvement of this result with higher statistics.

3. Measurement of the absolute branching ratio of $K^+ \rightarrow \pi^+ \pi^- \pi^+(\gamma)$

The measurement of $\text{BR}(K^+ \rightarrow \pi^+ \pi^- \pi^+(\gamma))$ completed the KLOE program of precise and fully inclusive measurements of K^\pm dominant branching ratios. It is the last result necessary for a global fit of K^\pm branching ratios with KLOE results but it is also an input required for the CUSP analysis done by the NA48 experiment to extract the $\pi\pi$ phase [4]. Moreover, the previous experimental result dates back to 1972 and provides no information on radiation cut-offs [5].

The analysis is performed using a sample of 174fb^{-1} of KLOE data. Two normalization samples are selected to contain self-triggering decays $K^- \rightarrow \mu^- \nu$ and $K^- \rightarrow \pi^- \pi^0$ which indicate the presence of K^+ in the second hemisphere of the detector thanks to the tagging possibility at KLOE. The K^+ decays are chosen for the BR measurement with tagging by K^- in order to minimize background from nuclear interactions whose cross-section at $p \approx 100\text{MeV}$ is a factor 10^3 smaller for K^+ . The track of tagging kaon is reconstructed in the DC and extrapolated backwards to obtain a virtual path of the signal kaon. In order to optimize the quality of the track reconstruction, kaons decaying before the Drift Chamber inner wall are selected, so that only their decay products enter the DC which minimizes the number of present tracks. Presence of at least two reconstructed tracks of pion candidates in an event is required. Number of signal events is obtained through a fit to the invariant mass spectrum of the third missing pion, separately for each of the normalization samples.

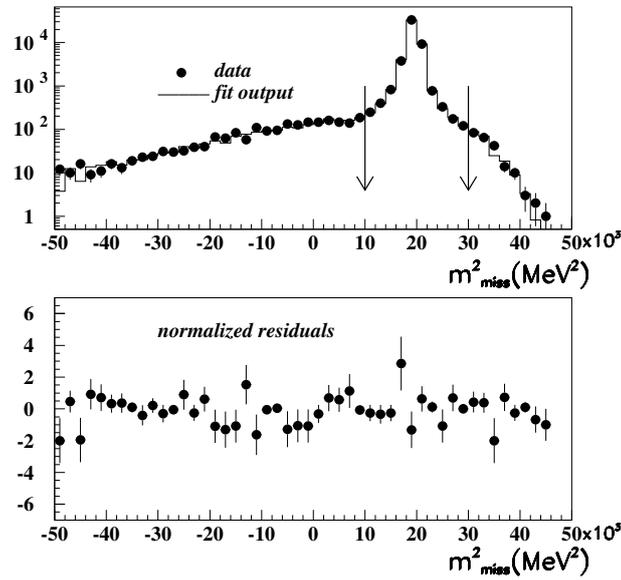


Figure 2: Fit of the MC to data for the missing mass spectrum obtained for the normalization sample tagged by $K^- \rightarrow \mu^- \nu$ decays.

Fig. 2 shows a result of the fit for the sample tagged by $K^- \rightarrow \mu^- \nu$. Signal events ($K \rightarrow 3\pi(\gamma)$) are counted in the missing mass region $10000\text{MeV}^2 < m_{\text{miss}}^2 < 30000\text{MeV}^2$. Finally, the branching

ratio is determined as the efficiency-corrected ratio:

$$\text{BR}(K^+ \rightarrow \pi^+ \pi^- \pi^+) = \frac{N_{K \rightarrow 3\pi}}{N_{\text{tag}}} \times \frac{1}{\varepsilon_{\text{sel}} C_{TB} C_f C_{\text{crv}}}, \quad (3.1)$$

where N_{tag} is the total size of the normalization sample, ε_{sel} is the selection efficiency and C_{TB} , C_f and C_{crv} are corrections for tag bias, machine background filter and cosmic ray veto, respectively.

The following results were obtained independently for the two normalization samples:

$$\text{BR}(K^+ \rightarrow \pi^+ \pi^- \pi^+(\gamma))|_{\text{Tag}K_{\mu 2}} = 0.05552 \pm 0.00034_{\text{stat}} \pm 0.00034_{\text{syst}}, \quad (3.2)$$

$$\text{BR}(K^+ \rightarrow \pi^+ \pi^- \pi^+(\gamma))|_{\text{Tag}K_{\pi 2}} = 0.05587 \pm 0.00053_{\text{stat}} \pm 0.00033_{\text{syst}}, \quad (3.3)$$

and were finally averaged yielding the final result [6]:

$$\text{BR}(K^+ \rightarrow \pi^+ \pi^- \pi^+(\gamma)) = 0.05565 \pm 0.00031_{\text{stat}} \pm 0.00025_{\text{syst}}, \quad (3.4)$$

whose precision is better than the previous measurement [5] by a factor of 5.

Moreover, the above result was used along with other K^\pm branching ratios and life-time determined by KLOE to perform a global fit with a unitary constraint. Results of the fit are presented in table 3.

Parameter	Value	Correlation coefficients					
$\text{BR}(K_{\mu 2}^\pm)$	0.6372(11)						
$\text{BR}(K_{\pi 2}^\pm)$	0.2070(9)	0.55					
$\text{BR}(\pi^\pm \pi^- \pi^+)$	0.0558(4)	-0.23	-0.05				
$\text{BR}(K_{e 3}^\pm)$	0.0498(5)	0.42	-0.15	0.06			
$\text{BR}(K_{\mu 3}^\pm)$	0.0324(4)	-0.39	0.14	-0.05	-0.58		
$\text{BR}(\pi^\pm \pi^0 \pi^0)$	0.01764(25)	-0.13	0.05	-0.02	0.04	-0.04	
τ_{K^\pm} (ns)	12.344(29)	0.20	0.19	-0.14	0.05	-0.04	0.02

Table 1: Results of the global fit of K^\pm branching ratios and life-time with KLOE measurements [6].

4. Conclusions and prospects for KLOE-2

The KLOE experiment provided a variety of Physics results, including interferometric tests of fundamental symmetries such as the CPT and Lorentz symmetry but also extensive measurements of kaon properties, finalized by the measurement of $\text{BR}(K^+ \rightarrow \pi^+ \pi^+ \pi^- (\gamma))$. The results on the Δa_μ parameters are the most precise results in the SME quark sector to date and several orders of magnitude better than for other meson systems. The $\text{BR}(K^+ \rightarrow \pi^+ \pi^+ \pi^- (\gamma))$ measurement along with previous KLOE results constitutes a consistent description of the K^\pm properties as was shown by the global unitary fit.

Recently an upgrade of KLOE has been performed. The improved KLOE-2 detector was equipped with several new subdetectors. Two pairs of new calorimeters were mounted at small angles around the beam pipe to increase acceptance for photons coming from the interaction point

[7, 8]. Moreover, the region around the interaction point was instrumented with a novel cylindrical GEM inner tracker which increases acceptance for low- p_T tracks and improves vertexing [9]. The improved vertex resolution for $K \rightarrow \pi^+ \pi^-$ is expected to increase the time resolution in the interferometric CPT and Lorentz symmetry test, and correspondingly the sensitivity on the Δa_μ parameters by a factor of 2, as well as on other QM and CPT violation parameters [10].

Along with the KLOE-2, the DAΦNE collider was upgraded to utilize a new crabbed-waist collision scheme enabling it to provide higher luminosity. KLOE-2 is now starting operations with a plan to collect data corresponding to an integrated luminosity $O(10\text{fb}^{-1})$ in 2-3 years.

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References

- [1] V. A. Kostelecky, *Formalism for CPT, T, and Lorentz violation in neutral meson oscillations*, Phys. Rev. D **64** (2001) 076001 [hep-ph/0104120].
- [2] O. W. Greenberg, *CPT violation implies violation of Lorentz invariance*, Phys. Rev. Lett. **89** (2002) 231602 [hep-ph/0201258].
- [3] D. Babusci *et al.* [KLOE-2 Collaboration], *Test of CPT and Lorentz symmetry in entangled neutral kaons with the KLOE experiment*, Phys. Lett. B **730** (2014) 89 [arXiv:1312.6818 [hep-ex]].
- [4] J. R. Batley *et al.* [NA48/2 Collaboration], *Observation of a cusp-like structure in the $\pi^0 \pi^0$ invariant mass distribution from $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decay and determination of the $\pi\pi$ scattering lengths*, Phys. Lett. B **633** (2006) 173 [hep-ex/0511056].
- [5] I. H. Chiang, J. L. Rosen, S. Shapiro, R. Handler, S. Olsen and L. Pondrom, *K^+ Decay in Flight*, Phys. Rev. D **6** (1972) 1254.
- [6] D. Babusci *et al.* [KLOE/KLOE-2 Collaboration], *Measurement of the absolute branching ratio of the $K^+ \rightarrow \pi^+ \pi^- \pi^+ (\gamma)$ decay with the KLOE detector*, Phys. Lett. B **738** (2014) 128 [arXiv:1407.2028 [hep-ex]].
- [7] M. Cordelli, G. Corradi, F. Happacher, M. Martini, S. Miscetti, C. Paglia, A. Saputi and I. Sarra *et al.*, *QCAL: A Tile calorimeter for KLOE-2 experiment*, Nucl. Instrum. Meth. A **617** (2010) 105 [arXiv:0906.1133 [physics.ins-det]].
- [8] M. Cordelli, E. Dane, S. Giovannella, M. Gatta, F. Happacher, A. Luca, S. Miscetti and A. Saputi *et al.*, *CCAL: A Crystal calorimeter with timing for the KLOE-2 upgrade*, Nucl. Instrum. Meth. A **718** (2013) 81.

- [9] A. Balla, G. Bencivenni, S. Cerioni, P. Ciambrone, E. De Lucia, G. De Robertis, D. Domenici and G. Felici *et al.*, *Status of the Cylindrical-GEM project for the KLOE-2 Inner Tracker*, Nucl. Instrum. Meth. A **628** (2011) 194 [arXiv:1003.3770 [physics.ins-det]].
- [10] G. Amelino-Camelia, F. Archilli, D. Babusci, D. Badoni, G. Bencivenni, J. Bernabeu, R. A. Bertlmann *et al.*, *Physics with the KLOE-2 experiment at the upgraded DAΦNE*, Eur. Phys. J. C **68** (2010) 619 [arXiv:1003.3868 [hep-ex]].