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CPT Symmetry Test at KLOE-2

E De Lucia for the KLOE-2 Collaboration
Laboratori Nazionali di Frascati dell'INFN, via E. Fermi 40, 00044 Frascati (RM), Italy
E-mail: erika.delucia@lnf.infn.it

Abstract. The entanglement in the neutral kaon pairs produced at the DAΦNE ϕ-factory is a unique tool to test discrete symmetries and quantum coherence at the utmost sensitivity, in particular strongly motivating the experimental searches of possible CPT violating effects, which would unambiguously signal New Physics. KLOE and KLOE-2 data sets with about 2.4×10^{10} ϕ-meson produced represent the largest sample ever collected at the ϕ-meson peak. The lepton charge asymmetry measured in K_S semileptonic decays with 1.7 fb^{-1} of KLOE data, improving the statistical uncertainty of present result by about a factor two, has been presented together with the test of CPT in transitions in $\phi \to K_S K_L \to \pi^{\pm}e^{\mp}\nu, 3\pi^0$ and $K_S K_L \to \pi^+\pi^-, \pi^{\pm}e^{\mp}\nu$ decays.

1. Introduction
KLOE-2 represents the continuation of KLOE [1] at the DAΦNE ϕ-factory at the INFN Laboratori Nazionali di Frascati [2], with a new physics program mainly focused on the study of K_S and η decays as well as on kaon interferometry, test of discrete symmetries, and search for physics beyond the Standard Model including also Dark photon hunting [3]. KLOE integrated 2.5 fb^{-1} running at the ϕ-meson peak and pursued several achievements in both precision kaon and hadron physics [1] playing a leading role in testing the CKM matrix unitarity measuring V$_{us}$ from both $K_{S,L}(l3)$ [4] and $K^+_{\mu 2}$ decays, in light-quark meson spectroscopy and pioneering the measurements of the $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$ cross section using initial state radiation, to shed light on the long-standing deviation of more than 3 σ's between the measured value of the anomalous magnetic moment of the muon, a_μ, and the Standard Model prediction.

The general purpose KLOE detector, composed of one of the biggest drift chamber [5] ever built surrounded by a lead-scintillating fiber Electromagnetic Calorimeter [6] among the best ones for energy and timing performance at low energies, underwent several upgrades. These include a state-of-the-art cylindrical GEM detector used for the first time in HEP experiments, the Inner Tracker [7], LET [8] and HET [9] taggers for $\gamma\gamma$ physics, and the CCALT and QCALT detectors [10], crystal and tile calorimeters positioned near the interaction point and along the beam-pipe respectively.

KLOE-2 data taking campaign ended successfully on March 30th 2018, with the total acquired luminosity milestone of at least 5 fb^{-1} fulfilled thanks to the combined effort of both KLOE-2 and DAΦNE teams. Together with the data set of its predecessor KLOE, the acquired data sample of about 8 fb^{-1} corresponds to 2.4×10^{10} ϕ-meson produced: the largest sample ever collected at the $\phi(1020)$ at e$^+$e$^-$ colliders. This will allow in particular to perform CPT symmetry and quantum coherence tests using entangled neutral kaons with an unprecedented precision.

2. Ks Semileptonic Charge Asymmetry

Among the cleanest and most precise CPT symmetry tests, the K_S semileptonic charge asymmetry measurement is performed by comparing the value of the lepton charge asymmetry $A_{S,L}$ for short- and long-lived neutral kaons with:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})} \quad (1)$$

with:

$$A_{S,L} = 2\left[Re\,(\epsilon_K) \pm Re\,(\delta_K) - Re(y) \pm Re(x_-)\right] \quad (2)$$

with $Re\,(\epsilon_K)$ and $Re\,(\delta_K)$ connected to T- and CPT-violation in the $K^0\bar{K^0}$ mixing, respectively, and $Re(y)$ and $Re(x_-)$ to CPT violation in $\Delta S = \Delta Q$ and $\Delta S \neq \Delta Q$ decay amplitudes, and all parameters implying CP violation. Any difference between A_S and A_L would imply CPT violating effects unambiguously signaling New Physics. On the other hand if CPT symmetry holds we would have $A_S = A_L = 2\,Re\,(\epsilon_K) \simeq 3\times10^{-3}$ each accounting for the CP impurity in the mixing in the corresponding physical state.

The difference $A_S - A_L = 4\times\,(Re\,\delta_K + Re\,x_-)$ represents a well constrained observable and based on the direct comparison of a transition probability with its CPT conjugated, through entangled neutral kaon pairs, can provide one of the most precise, robust and model independent tests of the CPT symmetry [11]. The sum $A_S + A_L = 4\times(Re\,\epsilon_K - Re\,y)$ can be used to extract the CPT-violating parameter $Re(y)$ once the measured value of $Re(\epsilon_K)$ is provided as input. The two combinations $A_S \pm A_L$ are a fundamental ingredient for improving the semileptonic decay contribution to the CPT test performed with the unitarity relationship, originally by Bell and Steinberger, which is providing the most stringent limits on $Im(\delta)$ and the mass difference $m(K^0) - m(\bar{K^0})$ [12, 13].

The most precise measurement of A_L has been performed by the KTeV collaboration: $A_L = (3.322 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}$ [14] while the first measurement of A_S was performed by the KLOE collaboration using 410 pb^{-1} of integrated luminosity: $A_S = (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \times 10^{-3}$ [15], with an accuracy dominated by the statistical uncertainty.

The KLOE-2 Collaboration has recently published a new measurement [16] with an integrated luminosity of 1.63 fb^{-1}. The best separation between signal and background components is obtained with the variable:

$$M^2(e) = [E_{K_S} - E(\pi) - E_\nu]^2 - p^2(e), \quad (3)$$

with E_{K_S} computed from the kinematics of $\phi \to K_S K_L$ two-body decay, knowing the ϕ-meson momentum (from Bhabha scattering events) and the reconstructed K_L direction, $E(\pi)$ evaluated from the measured track momentum in the pion mass hypothesis, and $E_\nu = |\vec{p}_{K_S} - \vec{p}(e) - \vec{p}(\pi)|$. $M^2(e)$ is calculated according to the TOF particle identification and for the signal events peaks to zero. Fig.1 shows the $M^2(e)$ distribution used for signal counting. The new result is: $A_S = (-4.9 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3}$ and improves the statistical accuracy of previous KLOE determination by almost a factor of two.

The combination of KLOE and KLOE-2 measurements is [16]:

$$A_S = (-3.8 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3} \quad (4)$$

where the correlation between both measurements has been taken into account. This result represents the most precise measurement of A_S up to date, approaching the level of the CP violation effects expected for K_S under the assumption of CPT invariance. A_S combined with the KTeV result on A_L and providing $Re(\delta_K)$ [12] and $Re(\epsilon_K)$ [13] as external inputs, allows

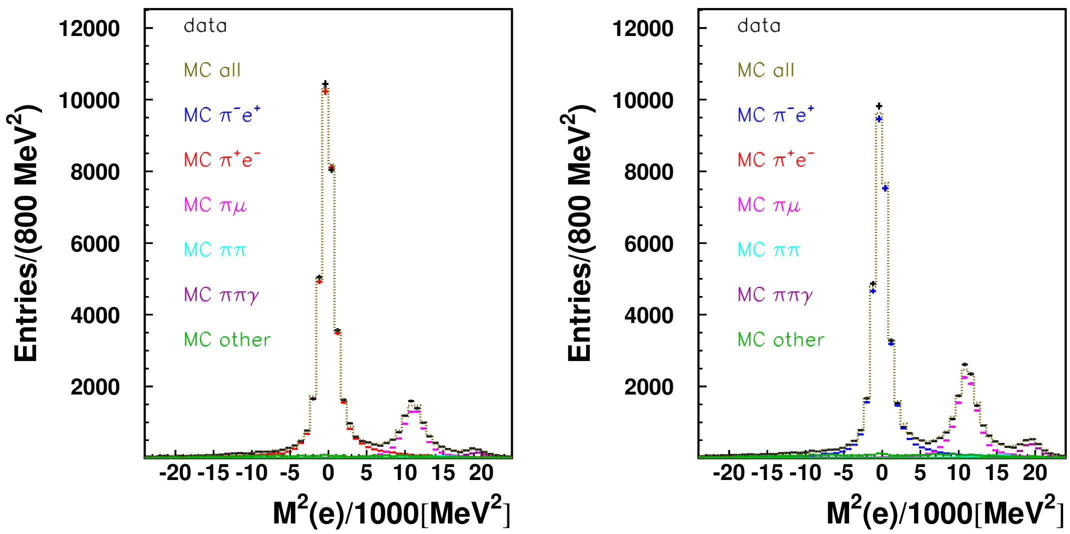

Figure 1. $M^2(e)$ distribution for data (black points) and MC simulation (dotted histogram) for both final charge states ($\pi^+ e^-$ – left side, $\pi^- e^+$ – right side) after the fit. Individual MC contributions are shown.

to extract new limits on the CPT-violating parameters: $Re(x_-) = (A_S$ - $A_L)/4$ - $Re(\delta_K)$ = (-2.0 $\pm$1.4) $\times$ 10^{-3} and $Re(y)$=$Re(\epsilon_K)$-(A_S + A_L)/4=(1.7 $\pm$1.4) $\times$ 10^{-3} which are consistent with CPT invariance and improve by almost a factor of two the previous results [15]. With the analysis of the full KLOE-2 data set, the uncertainty on A_S can be further reduced at the level of $\sim 3\times10^{-3}$.

3. Direct CPT test in Kaon transitions

Comparing neutral meson transition rates between flavour and CP eigenstates allows direct and model independent tests of time-reversal T and CPT symmetries [11] to be performed. Quantum entangled kaon pairs are used to identify the initial state of a particle transition by the decay of its entangled partner, while the final state is tagged by semileptonic and hadronic decays into two and three pions. Two T-violating observables are determined as ratios of the rates of two classes of processes identified in the dataset $K_S K_L \to \pi^\pm e^\mp \nu, 3\pi^0$ and $K_S K_L \to \pi^+\pi^-, \pi^\pm e^\mp \nu$:

$$R_2(\Delta t) = \frac{P[K^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to K^0(\Delta t)]} \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}, \tag{5}$$

$$R_4(\Delta t) = \frac{P[\bar{K^0}(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \bar{K^0}(\Delta t)]} \sim \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}, \tag{6}$$

where I(f_1,f_2;Δt) denotes the number of recorded events characterized by a time-ordered pair of kaon decays f_1 and f_2 separated by an interval of proper kaon decay times Δt [11]. A deviation of the asymptotic level of these ratios from unity for large transition times would be a T-violation manifestation.

Moreover CPT symmetry can be tested through the determination of the asymptotic level of the following double ratio:

$$\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{P[K^0(0) \to \mathrm{K}_-(\Delta t)]/P[\mathrm{K}_-(0) \to \bar{K^0}(\Delta t)]}{P[\bar{K^0} \to \mathrm{K}_-(\Delta t)]/P[\mathrm{K}_-(0) \to K^0(\Delta t)]} \stackrel{\Delta t \gg \tau_S}{=} 1 - 8Re(\delta_K) - 8Re(x_-), \tag{7}$$

where the δ_K and x_- are parameters violating the CPT symmetry in $K^0\bar{K}^0$ mixing and the $\Delta S = \Delta Q$ rule, respectively. This double ratio, referred to as $\mathrm{DR}_{\mathrm{CPT}}$, represents a robust CPT-violation sensitive observable [11] which has never been measured to date. A percent level accuracy was obtained on the double ratio measurement with 1.7 fb^{-1} KLOE data sample. The accuracy is expected to be reduced down to the 10^{-3} level of precision adding KLOE-2 data set.

4. Conclusions

KLOE and KLOE-2 data sets represent the largest sample ever collected at ϕ-meson peak. The entangled neutral kaon system at a ϕ-factory is a unique laboratory to study discrete symmetries. These tests are one of the key issues at KLOE-2 including several high precision tests of CPT and Quantum Mechanics. A new result on K_S Semileptonic Charge Asymmetry has been presented with a factor of 2 precision improvement with respect to previous results. The direct test of CPT in kaon transitions with $\mathrm{DR}_{\mathrm{CPT}}$ provides the cleanest CPT observable with 10^{-3} sensitivity with KLOE and KLOE-2 statistics. More physics results are to come from the analysis of the KLOE and KLOE-2 unique data set and not only from kaons.

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