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Recent results on Kaon Physics at KLOE-2

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Abstract. KLOE-2 extends the physics program of the forerunner KLOE experiment, especially in the field of discrete symmetries tests with neutral kaons. KLOE and KLOE-2 have collected together the largest sample of electron-positron collisions at an energy equal to the ϕ-meson mass, corresponding to about 2.4×10^{10} produced ϕ mesons.
The latest results on neutral kaon physics at KLOE will be reviewed, together with the status and prospects of the analyses of KLOE-2 data. A new measurement of the charge asymmetry in K_S semileptonic decays with 1.7 fb^{-1} of KLOE data, which improves the sensitivity of previous measurements of about a factor two, will be presented. Furthermore, the status of the analysis devoted to directly test $\mathcal{T}$ and $\mathcal{CPT}$ symmetries in neutral kaons transitions, as well as the search of the pure $\mathcal{CP}$-violating $K_S \to 3\pi^0$ decay using part of the recently acquired KLOE-2 dataset, will be presented.

1 Introduction

Flavoured neutral mesons are a powerful tool for testing fundamental discrete symmetries and their combinations such as $\mathcal{CP}$ and $\mathcal{CPT}$. Among them, neutral kaons are extensively used to search for manifestations of symmetry violations as they are easily translated to constraints on the properties of the mesons [1].

The KLOE experiment has contributed to determine most of the properties of neutral kaons as well as a number of tests of $\mathcal{CP}$ and $\mathcal{CPT}$ symmetries [2]. The KLOE dataset is still being analysed with the aim of obtaining more precise results on the charge asymmetry in semileptonic K_S decays and preforming a first direct $\mathcal{CPT}$ test in transitions of neutral kaons. Furthermore, the KLOE-2 experiment has ended its data taking on March 2018, collecting about 5 fb^{-1} of data, which will allow to enhance the upper limit set on the branching fraction of the pure $\mathcal{CP}$-violating decay $K_S \to 3\pi^0$ by KLOE.

2 KLOE and KLOE-2 experiments

KLOE and KLOE-2 have been operated at the DAΦNE ϕ-factory [3–5], which provided electron-positron collisions at the ϕ meson mass peak, $\sqrt{s} \approx 1020$ MeV. ϕ-meson decays into neutral kaons pairs – occurring with a branching fration of about 34% – were recorded by the KLOE apparatus, consisting of a huge cylindrical drift chamber (DC) [6], whose ~50 m^3

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volume is filled with Helium (90%) and Isobutane (10%), surrounded by a lead/scintillating-fiber sampling calorimeter (EMC), whose coverage is about 98% of the solid angle [7].

KLOE-2 additionally featured a cylindrical triple-GEM inner tracker [8] – installed close to the e^+e^- interaction point to improve vertex reconstruction for quantum interferometry studies [9] – and a system of calorimeters, devoted to enlarge the solid angle coverage of the EMC for detecting photons from $K_{S,L}$ decays and electrons/positrons from γ-γ processes.

KLOE and KLOE-2 datasets provide the largest sample of $e^+e^- \to \phi$ events, corresponding to about 24 billions of produced ϕ mesons.

3 $\mathcal{CPT}$ symmetry test with K_S semileptonic decays

A test of $\mathcal{CPT}$ symmetry can be performed by comparing the value of the lepton charge asymmetry, $A_{S,L}$, for short- and long-lived neutral kaons:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})} = 2\left[\Re(\epsilon) \pm \Re(\delta) - \Re(y) \pm \Re(x_-)\right], \quad (1)$$

where $\Re(\epsilon)$ and $\Re(\delta)$ are related to $\mathcal{T}$ and $\mathcal{CPT}$ violation in the K^0-$\overline{K^0}$ mixing, respectively, while $\Re(y)$ and $\Re(x_-)$ parametrize the $\mathcal{CPT}$ violation in $\Delta S = \Delta Q$ and $\Delta S \neq \Delta Q$ decay amplitudes, respectively [10]. If $\mathcal{CPT}$ symmetry is not violated, then the aforementioned asymmetries are expected to be identical: $A_S = A_L = 2\Re(\epsilon) \simeq 3 \times 10^{-3}$.

The charge asymmetry for K_L was precisely determined from the KTeV experiment at Fermilab: $A_L = (3.322 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}$ [11], while the most precise measurement of A_S was performed by the KLOE collaboration using 410 pb^{-1} of integrated luminosity collected in 2001-2002: $A_S = (1.5 \pm 9.6_{stat} \pm 2.9_{syst}) \times 10^{-3}$ [12].

The KLOE-2 Collaboration has recently published a new measurement based on a larger data sample, corresponding to an integrated luminosity of 1.63 fb^{-1} collected in 2004-2005 [13]: $A_S = (-4.9 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3}$, which improves the statistical accuracy of previous determination by almost a factor of two. Taking into account the correlation between both measurements, the combination of KLOE and KLOE-2 results is:

$$A_S = (-3.8 \pm 5.0_{stat} \pm 2.6_{syst}) \times 10^{-3}, \quad (2)$$

which represent the most precise measurement of A_S to date. This value, combined with KTeV result on A_L and providing also $\Re(\delta)$ [14] and $\Re(\epsilon)$ [15] as external inputs, allows to extract the $\mathcal{CPT}$-violating parameters [13]:

$$\begin{aligned} \Re(x_-) &= (-2.0 \pm 1.4) \times 10^{-3}, \\ \Re(y) &= (1.7 \pm 1.4) \times 10^{-3}, \end{aligned} \quad (3)$$

which are consistent with $\mathcal{CPT}$ invariance and improve by almost a factor of two the previous results [12].

The rare K_S decays are currently being studied using the full KLOE-2 dataset: with some 5 fb^{-1} total integrated luminosity a pure data sample of about 5×10^9 tagged K_S decays will be available.

4 Direct test of $\mathcal{T}$ and $\mathcal{CPT}$ in transitions of neutral kaons

The comparison of the rates of neutral mesons transitions between their flavour and $\mathcal{CP}$ eigenstates allows for a model independent test of $\mathcal{T}$ and $\mathcal{CPT}$ symmetries [16, 17]. Such a test –

up to date performed only in the case of neutral B mesons, where it delivered the first direct evidence of $\mathcal{T}$ violation [18] – is pursued with the K^0-$\overline{K^0}$ system at KLOE-2. To this extent, quantum entangled meson 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 $\mathcal{T}$ violating observables are determined as ratios between the rates of two classes of processes: $K_S K_L \to \pi^\pm e^\mp \nu, 3\pi^0$ and $K_S K_L \to \pi^+\pi^-, \pi^\pm e^\mp \nu$:

$$R_2(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_-(0) \to K^0(\Delta t)]} \sim \frac{I(\pi^+ e^- \bar{\nu}, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^- e^+ \nu; \Delta t)}, \tag{4}$$

$$R_4(\Delta t) = \frac{P[\overline{K^0}(0) \to K_-(\Delta t)]}{P[K_-(0) \to \overline{K^0}(\Delta t)]} \sim \frac{I(\pi^- e^+ \nu, 3\pi^0; \Delta t)}{I(\pi^+\pi^-, \pi^+ e^- \bar{\nu}; \Delta t)}, \tag{5}$$

where $I(f_1, f_2; \Delta t)$ denotes the number of recorded events characterized by a time-ordered pair of kaon decays f_1 and f_2 separate by an interval of proper kaon decay times Δt [16]. Any deviations of the asymptotic level of these ratios from unity for large transition times would be a manifestation of $\mathcal{T}$ violation.

The novel concept of such test can be generalized to test $\mathcal{CPT}$ symmetry through the determination of the asymptotic level of the following double ratio:

$$\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{P[K^0(0) \to K_-(\Delta t)]/P[K_-(0) \to \overline{K^0}(\Delta t)]}{P[\overline{K^0} \to K_-(\Delta t)]/P[K_-(0) \to K^0(\Delta t)]} \overset{\Delta t \gg \tau_S}{=} 1 - 8\Re\delta - 8\Re x_-, \tag{6}$$

where the δ and x_- are the parameters already presented in Equation 1. This double ratio constitutes a robust $\mathcal{CPT}$-violation-sensitive observable [17], which has never been measured.

The analysis tools required to determine both the $\mathcal{T}$-violation-sensitive ratios and the $\mathcal{CPT}$-violation-sensitive double ratio are being tested using the full KLOE dataset, corresponding to an integrated luminosity of about 1.7 fb^{-1}. A preliminary distribution of the ratio defined in Equation 6 is presented in Figure 1. Although the uncertainty on the asymptotic level of these observables available with KLOE data is only at the percent level, the analysis of the full KLOE-2 dataset will allow to perform statistically significant tests of $\mathcal{T}$ and $\mathcal{CPT}$ at the 10^{-3} level of precision.

5 Search for the pure $\mathcal{CP}$-violating $K_S \to 3\pi^0$ decay

Another class of $\mathcal{CP}$-violating phenomena in the neutral kaon system is represented by the decays of K_S into a $\mathcal{CP}$-asymmetric state with three pions. While the $K_S \to \pi^+\pi^-\pi^0$ process contains both $\mathcal{CP}$-violating and conserving amplitudes, the observation of the $K_S \to 3\pi^0$ decay would be a clear signature of $\mathcal{CP}$ violation. The present best upper limit has been set by KLOE at $BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ [19], still almost an order of magnitude lower than the precision of the Standard Model prediction (1.9×10^{-9}). Therefore, the search for $K_S \to 3\pi^0$ is already performed using the recently collected ~5 fb^{-1} of KLOE-2 data. With a larger data sample and an optimized analysis to properly treat KLOE-2 data, the sensitivity on this decay measurement is expected to be beyond the level of 10^{-8}.

6 Summary

The measurements of the KLOE detector have recently delivered the most precise result on the charge asymmetry in the semileptonic decays of the short-lived neutral K meson,

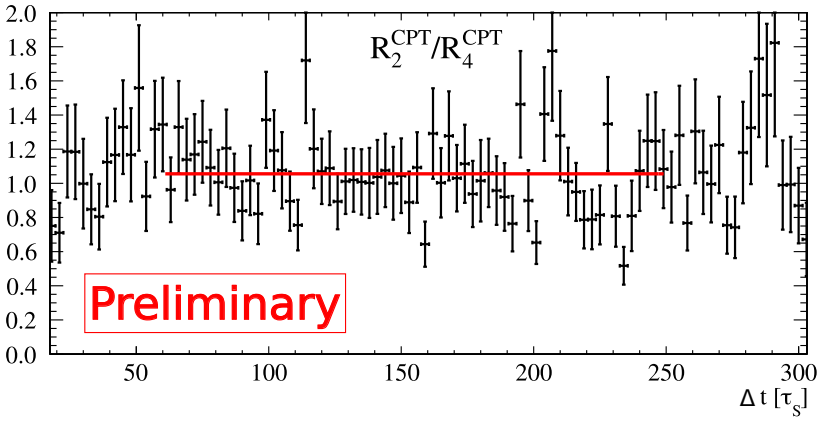

Figure 1. Preliminary distribution of the $\mathcal{CPT}$ violation-sensitive double ratio of neutral kaon double decay rates as a function of the time difference between entangled kaon decay times (Δt). The statistical uncertainty of the asymptotic level of this observable for $\Delta t \gg \tau_S$ (red line) amounts to 0.011 using the full KLOE dataset.

consistent with $\mathcal{CPT}$ conservation within the total uncertainty of $5.6{\times}10^{-3}$. The larger dataset collected by the upgraded KLOE-2 detector is expected to further improve the precision of this measurement to the level of 3×10^{-3}. The full datasets of KLOE is being used to perform a first direct tests of $\mathcal{T}$ and $\mathcal{CPT}$ symmetries in transitions of neutral kaons. Profiting also of KLOE-2 data, the precision on this novel tests is expected to reach the level of 10^{-3}. Finally, the search for the pure $\mathcal{CP}$-violating decay $K_S \to 3\pi^0$ is being performed with the full KLOE-2 dataset: The expected sensitivity to this process should allow KLOE-2 Collaboration to approach the level of the present Standard Model predicion for BR($K_S \to 3\pi^0$).

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