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 $\phi$-meson mass, corresponding to about $2.4\times10^{10}$ produced $\phi$ 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 $T$ and $CPT$ symmetries in neutral kaons transitions, as well as the search of the pure $CP$-violating $K_S \rightarrow 3\pi^0$ 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 $CP$ and $CPT$. 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 $CP$ and $CPT$ 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 $CPT$ 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 $CP$-violating decay $K_S \rightarrow 3\pi^0$ by KLOE.

2 KLOE and KLOE-2 experiments

KLOE and KLOE-2 have been operated at the DAΦNE $\phi$-factory [3–5], which provided electron-positron collisions at the $\phi$ meson mass peak, $\sqrt{s} \approx 1020$ MeV. $\phi$-meson decays into neutral kaons pairs – occurring with a branching fraction of about 34\% – were recorded by the KLOE apparatus, consisting of a huge cylindrical drift chamber (DC) [6], whose $\sim50$ m$^3$
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 $K_{S,L}$ decays and electrons/positrons from $\gamma\gamma$ processes.

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

3 CPT symmetry test with $K_S$ semileptonic decays

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

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

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

The charge asymmetry for $K_L$ was precisely determined from the KTeV experiment at Fermilab: $A_L = (3.322 \pm 0.058_{\text{stat}} \pm 0.047_{\text{syst}}) \times 10^{-3}$ [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: $A_S = (1.5 \pm 9.6_{\text{stat}} \pm 2.9_{\text{syst}}) \times 10^{-3}$ [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]: $A_S = (-4.9 \pm 5.7_{\text{stat}} \pm 2.6_{\text{syst}}) \times 10^{-3}$, 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:

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

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 $\Re(e)$ [15] as external inputs, allows to extract the CPT-violating parameters [13]:

$$\Re(x_-) = (-2.0 \pm 1.4) \times 10^{-3} ,$$

$$\Re(y) = (1.7 \pm 1.4) \times 10^{-3} ,$$

which are consistent with CPT invariance and improve by almost a factor of two the previous results [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 $5 \times 10^9$ tagged $K_S$ decays will be available.

4 Direct test of $T$ and CPT in transitions of neutral kaons

The comparison of the rates of neutral mesons transitions between their flavour and CPT eigenstates allows for a model independent test of $T$ and 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 $\bar{K}^0-K^0$ 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: $K_SK_L \to \pi^+e^+\nu$, $3\pi^0$ and $K_SK_L \to \pi^-\pi^0, \pi^+e^0\nu$:

$$R_2(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K_0(0) \to K^0(\Delta t)]} \sim \frac{I(\pi^0 e^- \bar{\nu}_e, 3\pi^0; \Delta t)}{I(\pi^+\pi^0, \pi^-e^+\nu; \Delta t)},$$

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

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 $\Delta t$ [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 $CPT$ symmetry through the determination of the asymptotic level of the following double ratio:

$$\frac{R_2^{CPT}}{R_4^{CPT}} = \frac{P[K^0(0) \to K_-(\Delta t)]/P[K^0(0) \to \bar{K}^0(\Delta t)]}{\Delta t^{\delta+\chi}} = 1 - 8\Re \delta - 8\Re \chi,$$

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

The analysis tools required to determine both the $\mathcal{T}$-violation-sensitive ratios and the $CPT$-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 $CPT$ at the $10^{-3}$ level of precision.

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

Another class of $CP$-violating phenomena in the neutral kaon system is represented by the decays of $K_S$ into a $CP$-asymmetric state with three pions. While the $K_S \to \pi^+\pi^-\pi^0$ process contains both $CP$-violating and conserving amplitudes, the observation of the $K_S \to 3\pi^0$ decay would be a clear signature of $CP$ 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 $CPT$ violation-sensitive double ratio of neutral kaon double decay rates as a function of the time difference between entangled kaon decay times ($\Delta t$). 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 $CPT$ conservation within the total uncertainty of $5.6\times10^{-3}$. The larger dataset collected by the upgraded KLOE-2 detector is expected to further improve the precision of this measurement to the level of $3\times10^{-3}$. The full datasets of KLOE is being used to perform a first direct tests of $T$ and $CPT$ 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 $CP$-violating decay $K_S \rightarrow 3\pi^0$ 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 prediction for BR($K_S \rightarrow 3\pi^0$).

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