Test of discrete symmetries with neutral kaons at KLOE-2

Antonio De Santis

Laboratori Nazionali di Frascati - INFN, v. Enrico Fermi 40, 00044, Frascati (RM) Italy.
E-mail: antonio.desantis@lnf.infn.it

Abstract. The KLOE-2 experiment at the INFN Laboratori Nazionali di Frascati (LNF) completed its data-taking at the $e^+e^-$ DAΦNE collider, which is implementing an innovative collision scheme based on a crab-waist configuration, and achieving the integrated luminosity goal of more than 5 fb$^{-1}$. KLOE-2 represents the continuation of KLOE with an upgraded detector and an extended physics program which includes neutral kaon interferometry and test of discrete symmetries among the main topics. Entangled neutral kaon pairs produced at DAΦNE are 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 constitute an unambiguous signal of a New Physics framework. The status of the latest ongoing analyses on KLOE/KLOE-2 data using the most refined analyses tools will be presented and discussed: (i) search for $CP$ violating $K_S \rightarrow 3\pi^0$ decay, (ii) measurement of the $K_S$ semileptonic charge asymmetry and tests of $CP$ and $CPT$ symmetry, (iii) test of Time reversal and CPT in transitions in $\phi \rightarrow K_SK_L \rightarrow \pi\nu, 3\pi^0, (2\pi)$ decays.

1. Introduction

DAΦNE, the Frascati $\phi$-factory, is an $e^+e^-$ collider working at a center of mass energy of $\sqrt{s} \sim 1020\text{MeV}$[1], corresponding to the peak of the $\phi$ resonance. The KLOE experiment at DAΦNE completed its first data taking campaign in March 2006 with a total integrated luminosity of $\sim 2.5\text{ fb}^{-1}$, corresponding to a production of $\sim 7.510^9 \phi$-mesons and $\sim 2.510^9 K_0\bar{K}_0$ pairs. After the KLOE run, DAΦNE has been upgraded implementing an innovative collision scheme based on a crab-waist configuration [2]. The KLOE-2 experiment [3], aiming to extend the physics program of its predecessor, completed the data-taking in March 2018 at the upgraded DAΦNE with an improved detector. The total integrated luminosity collected was $\sim 5.5\text{ fb}^{-1}$, as originally planned. The KLOE-2 physics program includes neutral kaon interferometry and tests of discrete symmetries and quantum mechanics as one of the main topics.

The properties of the neutral kaon system are directly related to the $CP$, $T$ and $CPT$ symmetries and provide the potential of performing very precise tests and to search for violation effects. Such tests can be further enhanced by using the quantum entanglement of neutral kaons produced by the $\phi$ decay, thus allowing for a wide field of quantum interferometry studies. The KLOE experiment, being the only experiment at $\phi$-factory’s, is the only candidate to study entangled neutral kaon pairs and is one of the most important contributors to the state of knowledge of kaon physics and related discrete symmetries violation.

1 on behalf of the KLOE-2 collaboration

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
2. The KLOE-2 experiment

The original KLOE detector consists of a large cylindrical drift chamber (DC) [4], which provides excellent momentum and vertex reconstruction for charged particles. DC is surrounded by a lead-scintillating fiber electromagnetic calorimeter (EMC) [5]. The energy deposits of charged and neutral particles in the calorimeter are measured with very good time resolution, allowing particle identification with time-of-flight (TOF) techniques. A superconducting coil around the EMC provides a 0.52 T axial field.

The upgrade of the KLOE detector consisted in the addition of an inner tracker (IT) based on cylindrical GEM technology for the improvement of tracking and decay vertex resolution close to the interaction point (IP)[6], a pair of crystal calorimeters inside the innermost part of the detector, close to IP, to increase the photon acceptance down to 8° [9] and a pair of scintillator/absorber detectors surrounding the beam pipe region inside the KLOE-2 experiment [10] to improve acceptance and efficiency for photons and pions coming from neutral kaon decays inside the detector volume.

3. $K_S$ meson physics measurements

A unique feature available working at $\phi$-factory is the possibility of identification of pure $K_S$ beam. The $K_S$ tagging is performed using the so-called $K_L$-crash technique: the identification of a $K_L$ interaction in the EMC. This special interaction is identified using both energy release and time information: a delayed neutral (not associated to extrapolated tracks in DCH) cluster in the EMC calorimeter with a minimal energy (usually 100 MeV) is identified as $K_L$-crash candidate.

3.1. Search for $K_S \to 3\pi^0$ decay

The Standard Model prediction for the branching ratio of the CP-violating decay $K_S \to 3\pi^0$ is $\text{BR}(K_S \to 3\pi^0) \sim 1.9 \times 10^{-9}$, making the direct observation of this decay really challenging. The best upper limit so far comes from the analysis of 1.7 fb$^{-1}$ collected by KLOE, using the $K_L$-crash to tag $K_S$ meson and searching for six photons coming from the IP [11]: $\text{BR}(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ at 90% C.L. This result is expected to be improved with the analysis of the additional 5.5 fb$^{-1}$ of data collected by KLOE-2. A preliminary analysis of 300 pb$^{-1}$ shows the good quality of KLOE-2 data even in presence of a larger machine background with respect to KLOE. The new experimental conditions forced to hardening the selection criteria, especially for the $K_L$-crash definition, in order to get stronger background rejection. This allowed to apply the same analysis scheme used in the previous measurement. At the end of the selection chain only one candidate event survives. Further improvements are expected allowing to reach a final sensitivity with the full statistics on the BR below $10^{-8}$.

3.2. $K_S$ Semileptonic charge asymmetry

The charge asymmetry in the neutral kaon decays ($A_{S/L}$ for $K_S$ and $K_L$ respectively) is related to parameters violating $CP$, $CPT$ and the $\Delta S = \Delta Q$ rule. A non-zero value for both asymmetries indicates $CP$ violation, while the observation of a discrepancy between them would imply a $CPT$ symmetry violation of some kind:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \nu)}{\Gamma(K_{S,L} \to \pi^- e^- \nu) + \Gamma(K_{S,L} \to \pi^+ e^+ \nu)} = [\text{Re} (\epsilon_K) \pm \text{Re} (\delta_K) - \text{Re} (y) \pm \text{Re} (x_-)]$$ (1)
with $Re(\epsilon_K)$ and $Re(\delta_K)$ implying $T$ and $CPT$-violation in the $K_0\bar{K}_0$ mixing, respectively, $Re(y)$ and $Re(x_-)$ implying $CPT$ violation in $\Delta S = \Delta Q$ and $\Delta S \neq \Delta Q$ decay amplitudes, respectively. All parameters implying $CP$ violation.

At present, the most precise measurement of $A_L$ has been performed by the KTeV collaboration: $A_L = (3.322 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}$ [12]. The measurement of its counterpart, $A_S$, requires a very pure $K_S$ beam which can only be realized at a $\phi$-factory as previously discussed and was measured previously at KLOE [13].

A new measurement [14], based on old KLOE dataset, has been obtained. The combination of the two KLOE results improves the statistical uncertainty and allows to set new limits on $Re(y)$ and $Re(x_-)$.

$K_S$ decay events were tagged by presence of a $K_L$-crash. Semileptonic decays were selected with an analysis of particle TOF from the decay point to the calorimeter. The residual background in the final sample obtained after event selection was estimated performing a MC-based event counting. Semileptonic $K_S$ decays were counted in a selected region of the variable: $M^2 = [E(K_S) - E(\pi) - E(\nu)]^2 - p^2(e)$, that goodly split the signal and background regions as shown in Fig. 1. MC-simulated $M^2$ distributions for signal ($K_S \rightarrow \pi^+ e^+ \nu$) and major background components were fitted to the spectrum obtained from experimental data.

![Figure 1](image)

**Figure 1.** $M^2(e)$ distribution for data (black points) and MC simulation (dotted histogram) for both final charge states: $\pi^+ e^-$ (left), $\pi^- e^+$ (right) after the fit. Separated MC contributions are shown with different colors (figure coloured online).

The numbers of semileptonic decay events obtained from the fit were $34579 \pm 251$ for $K_S \rightarrow \pi^- e^+ \nu$ and $36874 \pm 255$ for $K_S \rightarrow \pi^+ e^- \nu$, resulting in the following value of the charge asymmetry:

$$A_S = (-4.9 \pm 5.7_{stat} \pm 2.6_{syst}) \times 10^{-3};$$

consistent with the previous determination on an independent data sample and improving the statistical accuracy by almost a factor of two. Taking into account the correlations of the systematical uncertainties of both measurements, based on similar analysis schemes, their combination provides:

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

The combined result 3 together with the KTeV result on $A_L$ [12] yields for the sum and difference of asymmetries: $(A_S - A_L)/4 = Re(\delta_K) + Re(x_-) = (-1.8 \pm 1.4) \times 10^{-3}$ and $(A_S + A_L)/4 = Re(\epsilon_K) - Re(y) = (-0.1 \pm 1.4) \times 10^{-3}$. Using $Re(\delta_K) = (2.5 \pm 2.3) \times 10^{-4}$ [15].
and $Re(\epsilon_K) = (1.596 \pm 0.013) \times 10^{-3}$ [16] the $CPT$ violating parameters $Re(x_-)$ and $Re(y)$ are extracted:

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

which are consistent with $CPT$ invariance and improve by almost a factor of two the previous results [13].

4. $CPT$ symmetry test in transition amplitudes

As stated in the introduction, a different approach to the kaon physics is possible at $\phi$–factory, based on the observation of the time evolution of the system correlation. The quantum mechanics description of the $\phi \to K_S K_L$ decay implies a anti-correlated initial state that is expected to evolve in time preserving this characteristics. This feature has been already exploited to perform several tests and measurements on the kaon system [17, 18]. Kaon correlation could be also used to tag CP or Flavor eigenstate during the time evolution of the initial state [19]. A comparison of the rates of neutral mesons transitions between their flavor and $CP$ eigenstates allows for a model independent test of the $T$ and $CPT$ symmetries. Such a test has been performed already in the case of neutral B mesons obtaining the first direct evidence of $T$ violation [20].

![Figure 2. Preliminary distribution of the CPT-violation sensitive double ratio of neutral kaon double decay rates as a function between entangled kaon decay times difference ($\Delta t$) as in Eq. 5. The statistical uncertainty of the asymptotic level of this observable for $\Delta t \gg \tau_S$ (red line) amounts to 0.011 with the KLOE dataset (2 fb$^{-1}$).](image)

Similar approach is pursued with the $K_0\overline{K}_0$ system at KLOE-2. In this novel test, 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 decays and hadronic decays into two and three pions, to identify Flavor or $CP$ eigenstate, respectively. $T$ (Eq. 4) and $CPT$ (Eq. 5) violating observables are determined as ratios of the rates of two classes of processes identified in the KLOE dataset: $K_S K_L \to \pi^\pm e^\mp \nu$ and $K_S K_L \to \pi^+\pi^- \pi^\pm e^\mp \nu$:

$$
R_2(\Delta t) = \frac{P(K_0(0) \to K_- (\Delta t)) \sim I(l^-, 3\pi^0; \Delta t)}{P(K_- (0) \to K_0(\Delta t)) \sim I(\pi\pi, l^+\Delta t)}
$$

$$
R_4(\Delta t) = \frac{P(K_0(0) \to K_- (\Delta t)) \sim I(l^+, 3\pi^0; \Delta t)}{P(K_- (0) \to K_0(\Delta t)) \sim I(\pi\pi, l^-\Delta t)}
$$

$$
R_2^{CPT}(\Delta t) = \frac{P(K_0(0) \to K_- (\Delta t)) \sim I(l^-, 3\pi^0; \Delta t)}{P(K_- (0) \to K_0(\Delta t)) \sim I(\pi\pi, l^-\Delta t)}
$$
\[ R_{4}^{\text{CPT}}(\Delta t) = \frac{P(\bar{K}_{0}(0) \rightarrow K_{-}(\Delta t))}{P(K_{-}(0) \rightarrow \bar{K}_{0}(\Delta t))} \sim \frac{I(l^{+},3\pi^{0};\Delta t)}{I(\pi\pi,l^{+}\Delta t)} \]

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 \( \Delta t \). A deviation of the asymptotic level of these ratios from unity for large transition times would be a T or CPT violation manifestation. A preliminary result is shown in Fig. 2, where the ratio of the Eq. 5 is plotted.

5. Conclusions

The measurements of the KLOE detector have recently delivered the most precise result on the charge asymmetry in the semileptonic decays of the \( K_{S} \) meson, consistent with CPT conservation within the total uncertainty of \( 5.6 \times 10^{-3} \). The larger dataset collected recently by the upgraded KLOE-2 detector is expected to further improve the precision of this measurement to the level of \( 3 \times 10^{-3} \). The datasets of KLOE and KLOE-2 are also used to perform first direct tests of the T and CPT symmetries in transitions of neutral kaons, expected to reach the precision of \( 10^{-3} \). Finally, the search for the CP-violating decay \( K_{S} \rightarrow 3\pi^{0} \) is performed with the KLOE-2 dataset and a new result on its branching ratio is likely to be the first physics result obtained with KLOE-2.

Acknowledgments

We warmly thank our former KLOE colleagues for the access to the data collected during the KLOE data taking campaign. We thank the DANE team for their efforts in maintaining low background running conditions and their collaboration during all data taking. We want to thank our technical staff: G.F. Fortugno and F. Sborzacchi for their dedication in ensuring efficient operation of the KLOE computing facilities; M. Anelli for his continuous attention to the gas system and detector safety; A. Balla, M. Gatta, G. Corradi and G. Papalino for electronics maintenance; C. Piscitelli for his help during major maintenance periods. This work was supported in part by the Polish National Science Centre through the Grants No. 2013/11/B/ST2/04245, 2014/14/E/ST2/00262, 2014/12/S/ST2/00459, 2016/21/N/ST2/01727, 2016/23/N/ST2/01293, 2017/26/M/ST2/00697.

References

[1] Gallo A et al. 2006 Conf. Proc. C 060626 604-606 SLAC-PUB-12093.
[2] Zobov M et al. 2010 Phys. Rev. Lett. 104 174801; Milardi C et al. 2012 JINST 7 T03002.
[3] Amelino-Camelia G. et al. 2010 Eur. Phys. J. C 68 619.
[4] Adinolfi M et al. 2002 Nucl. Instrum. Meth. A 488 51.
[5] Balla A et al. 2014 JINST 9 C01014.
[6] Babusci D et al. 2010 Nucl. Instrum. Meth. A 617 81.
[7] Archilli F et al. 2010 Nucl. Instrum. Meth. A 617 266.
[8] Cordelli M et al. 2013 Nucl. Instrum. Meth. A 718, 81.
[9] Babusci D et al. 2013 Phys. Lett. B 723 54.
[10] Alavi-Harati A et al. 2002 Phys. Rev. Lett. 88 181601.
[11] Ambrosino F et al. 2006 Phys. Lett. B 636 173.
[12] Anastasi A et al. 2018 JHEP 1809 021.
[13] Patrignani C et al. 2016 Chin. Phys. C 40 no.10, 100001.
[14] Ambrosino F et al. 2006 JHEP 0612 011.
[15] Ambrosino F et al. 2006 Phys. Lett. B 642 315.
[16] Babusci D et al. 2014 Phys. Lett. B 730 89.
[17] Bernabeu J, Di Domenico A and Villanueva-Perez P 2013 Nucl. Phys. B 868 102.
[18] Lees J P et al. 2012 Phys. Rev. Lett. 109 211801.