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MEASUREMENT OF THE CHARGE ASYMMETRY FOR THE $K_{\rm S} \to \pi e \nu$ DECAY AND TEST OF CPT SYMMETRY WITH THE KLOE DETECTOR*

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Studies presented in this paper were conducted using 1.63 fb^{-1} of integrated luminosity collected by the KLOE experiment. The excellent time resolution of the electromagnetic calorimeter and the very good accuracy on both momentum and vertex reconstruction of the tracking system allow to reconstruct about 7×10^4 $K_{\rm S} \to \pi^{\pm} e^{\mp} \nu$ decays. The measured value of the charge asymmetry for this decay is $A_{\rm S} = (-4.9 \pm 5.7_{\rm stat} \pm 2.6_{\rm syst}) \times 10^{-3}$, which is almost twice more precise than the previous KLOE result. The combination of these two measurements gives $A_{\rm S} = (-3.8 \pm 5.0_{\rm stat} \pm 2.6_{\rm syst}) \times 10^{-3}$ and, together with the asymmetry of the $K_{\rm L}$ semileptonic decay, provides significant tests of the CPT symmetry. The obtained results are in agreement with CPT invariance.

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1. Introduction

Investigations of the neutral kaon system, due to the system's sensitivity to a variety of discrete symmetries such as charge conjugation (C), parity (P) and time reversal (T), allow to test the CPT symmetry as well as basic principles of the Standard Model. Specifically, this paper focuses on the difference and sum of charge asymmetries for the short-lived kaon ($A_{\rm S}$) and the long-lived kaon ($A_{\rm L}$) to search for CPT symmetry violation.

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2. Semileptonic decays of neutral kaons

The physical states K_{S} and K_{L} are defined as [1]

$$\begin{aligned} \left|K_{\mathrm{S/L}}\right\rangle &= \frac{1}{\sqrt{2\left(1+|\epsilon_{\mathrm{S/L}}|^2\right)}}\left(\left(1+\epsilon_{\mathrm{S/L}}\right)\left|K^0\right\rangle \pm \left(1-\epsilon_{\mathrm{S/L}}\right)\left|\bar{K}^0\right\rangle\right) , \\ \epsilon_{\mathrm{S/L}} &= \epsilon_K \pm \delta_K , \end{aligned} \tag{1}$$

where ϵ_K and δ_K are parameters describing CP or CPT violation, respectively.

In order to describe semileptonic kaon decays ($K \to \pi e \nu$), due to Eq. (1), only four amplitudes have to be taken into account. The corresponding semileptonic amplitudes are shown in Table I. According to the Standard Model, the decay of K^0 (or $\bar{K}^0$) state is associated with the transition of the $\bar{s}$ quark into $\bar{u}$ quark (or s into u) and emission of the charged boson. Change of strangeness (ΔS) implies the corresponding change of electric charge (ΔQ). This is the so-called $\Delta S = \Delta Q$ rule. Therefore, the decays of $K^0 \to \pi^- e^+ \nu$ and $\bar{K}^0 \to \pi^+ e^- \bar{\nu}$ are present but $K^0 \to \pi^+ e^- \bar{\nu}$ and $\bar{K}^0 \to \pi^- e^+ \nu$ are not. This implies that, if $\Delta S = \Delta Q$ rule is conserved, then parameters $\mathcal{A}_-$ and $\bar{\mathcal{A}}_+$ vanish.

TABLE I

Semileptonic decays and its amplitudes. H_{weak} stands for a part of Hamiltonian corresponding to the weak interaction.

Decay	Matrix element parametrization	According to the $\Delta S = \Delta Q$
$K^0 \to \pi^- e^+ \bar{\nu}$	$\langle \pi^- e^+ \nu \vert H_{\mathrm{weak}} \left\vert K^0 \right\rangle = \mathcal{A}_+$	allowed
$\bar{K}^0 \to \pi^+ e^- \nu$	$\langle \pi^+ e^- \bar{\nu} \vert H_{\mathrm{weak}} \left\vert \bar{K}^0 \right\rangle = \bar{\mathcal{A}}_-$	allowed
$K^0 \to \pi^+ e^- \nu$	$\langle \pi^+ e^- \bar{\nu} \vert H_{\mathrm{weak}} \left\vert K^0 \right\rangle = \mathcal{A}_-$	not allowed
$\bar{K}^0 \to \pi^- e^+ \bar{\nu}$	$\langle \pi^- e^+ \nu \vert H_{\mathrm{weak}} \left\vert \bar{K}^0 \right\rangle = \bar{\mathcal{A}}_+$	not allowed

For further consideration, it is useful to introduce the parameters x, $\bar{x}$, $x_\pm$, y

$$x = \frac{\bar{\mathcal{A}}_+}{\mathcal{A}_+} , \qquad \bar{x} = \left(\frac{\mathcal{A}_-}{\bar{\mathcal{A}}_-}\right)^* , \qquad x_\pm = \frac{x \pm \bar{x}^*}{2} , \qquad y = \frac{\bar{\mathcal{A}}_-^* - \mathcal{A}_+}{\bar{\mathcal{A}}_-^* + \mathcal{A}_+} ,$$

and obtain relations between them and discrete symmetries (see Table II).

TABLE II

Relations between discrete symmetries and semiletponic amplitudes.

Conserved quantity	Required relation
$\Delta S = \Delta Q$ rule	$x = \bar{x} = 0$
CPT symmetry	$x = \bar{x}^*\,, \quad y = 0$
CP symmetry	$x = \bar{x}\,, \quad y =$ imaginary
T symmetry	$y =$ real

3. Charge asymmetry and experimental verification

The introduced parameters could be associated with the $K_{\rm S}$ and $K_{\rm L}$ semileptonic decay widths through the charge asymmetry ($A_{\rm S,L}$)

$$\begin{aligned} A_{\rm S,L} &= \frac{\Gamma(K_{\rm S,L} \to \pi^- e^+ \nu) - \Gamma(K_{\rm S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{\rm S,L} \to \pi^- e^+ \nu) + \Gamma(K_{\rm S,L} \to \pi^+ e^- \bar{\nu})} \\ &= 2\left[\mathrm{Re}\left(\epsilon_{\rm S,L}\right) - \mathrm{Re}(y) \pm \mathrm{Re}(x_-)\right] . \end{aligned}$$

Sum and difference of the $A_{\rm S}$ and $A_{\rm L}$ allow to search for the CPT symmetry violation, either in the decay amplitudes through the parameter y (see Table II) or in the mass matrix through the parameter δ_K

$$\begin{aligned} A_{\rm S} + A_{\rm L} &= 4\,\mathrm{Re}(\epsilon) - 4\,\mathrm{Re}\,(y)\ , \\ A_{\rm S} - A_{\rm L} &= 4\,\mathrm{Re}(\delta_K) + 4\,\mathrm{Re}\,(x_-)\ . \end{aligned} \tag{2}$$

At present, the most precise measurement of $A_{\rm L}$ has been performed by the KTeV Collaboration: $A_{\rm L} = (3.322 \pm 0.058_{\rm stat} \pm 0.047_{\rm syst}) \times 10^{-3}$ [2]. The measurement of its counterpart, $A_{\rm S}$, requires a very pure $K_{\rm S}$ beam which can only be realised exploiting the entangled neutral kaons pairs produced at a ϕ-factory. The first measurement of $A_{\rm S}$ has been performed by the KLOE Collaboration using 410 pb^{-1} of integrated luminosity collected at DAΦNE, the ϕ-factory of the INFN laboratories of Frascati: $A_{\rm S} = (1.5 \pm 9.6_{\rm stat} \pm 2.9_{\rm syst}) \times 10^{-3}$ [3], with an accuracy dominated by the statistical uncertainty. The new measurement reported here is based on a four times larger data sample, corresponding to an integrated luminosity of 1.63 fb^{-1} collected in 2004–2005.

The measurement is based on the ability to tag a $K_{\rm S}$ meson by identifying the $K_{\rm L}$ meson. The KLOE detector consists of two main parts: a drift chamber [4] and a barrel shaped electromagnetic calorimeter [5], both inserted into a magnetic field (0.52 T). Around 60% of $K_{\rm L}$ mesons reach the electromagnetic calorimeter and can be identified by their energy deposition inside it. The selection of $K_{\rm S} \to \pi e \nu$ decays requires a vertex reconstructed near the Interaction Point with two tracks that belong to two oppositely charged particles. These particles must reach the calorimeter and deposit energy inside it in order to use the Time-of-Flight technique. This technique aims at rejecting background, which consists mainly of $K_{\rm S} \to \pi\pi$ events, and at identifying the final charged states ($\pi^+ e^- \bar{\nu}$ and $\pi^- e^+ \nu$).

4. Result and prospects for KLOE-2

The measured value of the charge asymmetry for this decay is [6, 7]

$$A_{\rm S} = (-4.9 \pm 5.7_{\rm stat} \pm 2.6_{\rm syst}) \times 10^{-3}\,, \tag{3}$$

which is almost twice more precise than the previous KLOE result. The combination of these two measurements gives $A_{\rm S} = (-3.8 \pm 5.0_{\rm stat} \pm 2.6_{\rm syst}) \times 10^{-3}$ and, together with the asymmetry of the $K_{\rm L}$ semileptonic decay, provides significant tests of the CPT symmetry. The CPT violating parameters ${\rm Re}(x_-)$ and ${\rm Re}(y)$ are extracted

$$\begin{aligned} {\rm Re}(x_-) &= (-2.0 \pm 1.4) \times 10^{-3}\,, \\ {\rm Re}(y) &= (1.7 \pm 1.4) \times 10^{-3}\,, \end{aligned} \tag{4}$$

which are consistent with CPT invariance and improve by almost a factor of two the previous results [3].

KLOE-2 provides not only larger statistics of 5.5 fb^{-1} but also improved event reconstruction due to the Inner Tracker detector made out in a novel GEM technology [8]. The analysis of KLOE-2 data would allow to reach the statistical uncertainty of 3×10^{-3} [9].

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