Search for CPT and Lorentz-Symmetry Violation in Entangled Neutral Kaons

Antonio Di Domenico

* Dipartimento di Fisica, Sapienza Università di Roma and INFN Sezione di Roma
  P. le A. Moro 2, I-00185, Rome, Italy

The neutral-kaon system constitutes a fantastic and unique laboratory for the study of CPT symmetry and the basic principles of quantum mechanics, and a $\phi$-factory represents a unique opportunity to push forward these studies. The experimental results show no deviation from the expectations of quantum mechanics and CPT symmetry, while the extreme precision of the measurements, in some cases, reaches the interesting Planck-scale region. At present the KLOE-2 experiment is collecting data with an upgraded detector with the aim of significantly improving these kinds of experimental tests.

1. Introduction

A violation of CPT symmetry would have a dramatic impact on our present theoretical picture and would definitely constitute an unambiguous signal of a new physics framework, thus strongly motivating both experimental searches and theoretical studies on this subject. In attempts to discuss quantum-gravity scenarios, speculative theoretical models have been considered which may exhibit a CPT-symmetry breakdown.1,2 Among them a general theoretical possibility for CPT violation is provided by the Standard-Model Extension (SME), based on spontaneous breaking of Lorentz symmetry,3 which appears to be compatible with the basic tenets of quantum field theory and retains gauge invariance and renormalizability.

The neutral-kaon doublet is one of the most intriguing systems in nature. During its time evolution a neutral kaon oscillates between its particle and antiparticle states with a beat frequency $\Delta m \approx 5 \times 10^9 \mathrm{s}^{-1}$ ($\approx 3 \times 10^{-15} \text{ GeV}$), where $\Delta m$ is the tiny mass difference between the two physical states $K_L$ and $K_S$, exponentially decaying with very different lifetimes, $\tau_L \gg \tau_S$. The fortunate coincidence that $\Delta m$ is about half the decay width of $K_S$ allows observing a variety of intricate quantum interference phenomena in the time evolution and decay of neutral kaons.
At a $\phi$-factory neutral-kaon pairs are produced in a pure antisymmetric entangled state, offering new and unique possibilities to study the discrete symmetries and the basic principles of quantum mechanics. What makes the entangled $K^0\bar{K}^0$ pair a really unique system, even with respect to other similar neutral-meson systems ($B^0, B^0_s, \text{and } D^0$), is the presence of peculiar and strong amplification mechanisms in the CPT-violation observables. At a $\phi$-factory the precision of the measurements in some cases can reach the level of the interesting Planck-scale region, i.e., $O(m_K^2/M_{\text{Planck}}) \sim 2 \times 10^{-20}$ GeV, which is a very remarkable level of accuracy.

2. “Standard” CPT test from unitarity

The complex parameter $\delta$ describes CPT violation in $K^0-\bar{K}^0$ mixing, and it is proportional to the particle-antiparticle mass and width difference:

$$\delta = \frac{1}{2} \frac{(m_{K^0} - m_{\bar{K}^0}) - i(\Gamma_{K^0} - \Gamma_{\bar{K}^0})/2}{\Delta m + i\Delta \Gamma/2}. \quad (1)$$

The real part of $\delta$ was measured by CPLEAR studying the time behaviour of semileptonic decays from initially tagged $K^0$ and $\bar{K}^0$ mesons, while the imaginary part can be bounded imposing the unitarity condition. The limits on $\delta$ can be used to constrain the mass and width difference between $K^0$ and $\bar{K}^0$. For $\Gamma_{K^0} - \Gamma_{\bar{K}^0} = 0$, i.e., neglecting CPT-violating effects in the decay amplitudes, Eq. (1) translates into the best bound on the fractional mass difference: $|m_{K^0} - m_{\bar{K}^0}| < 4.0 \times 10^{-19}$ GeV at 95% C.L. It is worth noting that this stringent limit is obtained thanks to the amplifying effect of the denominator in Eq. (1), due to the tiny mass and width difference between the physical states $K_S$ and $K_L$.

3. CPT- and Lorentz-symmetry tests

In the SME for neutral kaons, CPT violation manifests to lowest order only in the mixing parameter $\delta$, (e.g., vanishes at first order in the decay amplitudes), and exhibits a dependence on the 4-momentum of the kaon:

$$\delta \approx i \sin \phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \beta_K \cdot \Delta \vec{a})/\Delta m, \quad (2)$$

where $\gamma_K$ and $\beta_K$ are the kaon boost factor and velocity in the observer frame, $\phi_{SW}$ is the so called superweak phase, and $\Delta a_\mu$ are four CPT- and Lorentz-violating coefficients for the two valence quarks in the kaon.

By studying the interference pattern of the entangled neutral kaon pairs in the $\phi \to K^0\bar{K}^0 \to \pi^+\pi^-\pi^+\pi^-$ final state, as a function of sidereal
time and particle direction in celestial coordinates, the KLOE collaboration obtained the following results: 

\[ \Delta a_0 = (-6.0 \pm 7.7_{\text{stat}} \pm 3.1_{\text{syst}}) \times 10^{-18} \text{ GeV}, \]

\[ \Delta a_X = (0.9 \pm 1.5_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-18} \text{ GeV}, \]

\[ \Delta a_Y = (-2.0 \pm 1.5_{\text{stat}} \pm 0.5_{\text{syst}}) \times 10^{-18} \text{ GeV}, \]

\[ \Delta a_Z = (3.1 \pm 1.7_{\text{stat}} \pm 0.5_{\text{syst}}) \times 10^{-18} \text{ GeV}. \] (3)

These results constitute the most sensitive measurements in the quark sector of the SME, and can be compared to similar results obtained in the \( B \) and \( D \) meson systems, where an accuracy of \( \mathcal{O}(10^{-15} \text{ GeV}) \) and \( \mathcal{O}(10^{-13} \text{ GeV}) \), respectively, has been reached.\(^{10,11}\)

4. Search for decoherence and CPT-violation effects

The quantum interference between the two kaons initially in the entangled state and decaying in the CP-violating channel \( \phi \rightarrow K_SK_L \rightarrow \pi^+\pi^- \pi^+\pi^- \), has been observed for the first time by the KLOE collaboration.\(^{12,13}\) The decoherence parameter has been measured:

\[ \zeta_{00} = (1.4 \pm 9.5_{\text{stat}} \pm 3.8_{\text{syst}}) \times 10^{-7}, \] (4)

compatible with the prediction of quantum mechanics \( \zeta_{00} = 0 \) and no decoherence effect. This constitutes the most precise quantum coherence test for an entangled system, due to the peculiar CP-violation suppression present in this specific decay channel, which naturally amplifies the sensitivity of the decoherence effect.

A model for decoherence can be formulated\(^{14}\) in which neutral kaons are described by a density matrix \( \rho \) that obeys a modified Liouville-von Neumann equation. In this context \( \gamma \) is one of the relevant parameters signalling decoherence and CPT violation.\(^{15}\) It has mass units and in a quantum-gravity scenario it is presumed to be at most of \( \mathcal{O}(m_K^2/M_{\text{Planck}}) \sim 2 \times 10^{-20} \text{ GeV} \). The KLOE collaboration obtained the following result\(^{13}\) compatible with no CPT violation:

\[ \gamma = (0.7 \pm 1.2_{\text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-21} \text{ GeV}, \] (5)

while the sensitivity reaches the interesting region.

5. Direct CPT test in transition processes

A novel CPT test has been recently studied in the neutral-kaon system based on the direct comparison of a transition probability with its CPT reverse transition.\(^{16}\) The appropriate preparation and detection of \( \text{in} \) and \( \text{out} \)
states in both the reference and the reverse processes is made by exploiting
the entanglement of neutral kaons produced in a $\phi$-factory and using their
decays as filtering measurements of the kaon states. The test can be easily
implemented at KLOE and KLOE-2, while in the $B$-meson system a similar
test has been performed.\(^\text{17}\)

6. Conclusions and perspectives

The parameters related to several possible CPT violations effects, including
decoherence and Lorentz-symmetry breaking effects which might be justi-
fied in a quantum-gravity framework, have been measured in the neutral-
kaon system in some cases with a precision that very interestingly reaches
the Planck scale region.

The KLOE physics program is continuing with the KLOE-2 experiment,
presently taking data at the DAΦNE facility with an upgraded detector.\(^\text{18}\)
Significant improvements are expected in all these CPT tests.

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