# CPT symmetry, quantum gravity, and entangled neutral K mesons

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$CPT$ appears as the only inversion symmetry transformation under which the laws of nature are strictly invariant. This fact has a very solid theoretical ground in the $CPT$ theorem, and any violation of the $CPT$ symmetry would unambiguously represent a signal of a New Physics framework. The entangled neutral kaon system at a $\phi$-factory offers a unique possibility to perform a variety of fundamental tests of $CPT$ invariance, as well as of the basic principles of quantum mechanics. The KLOE experiment at the DAΦNE collider put stringent limits on several kinds of possible $CPT$ violation and decoherence mechanisms, which might be justified in a quantum gravity framework. No deviation from the expectations of quantum mechanics and $CPT$ symmetry is observed, 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 improve this kind of experimental tests.

*Keywords*: CPT symmetry; discrete symmetries; neutral kaons; $\phi$-factory; quantum gravity.



## 1. Introduction

The three discrete symmetries of quantum mechanics, $C$ (charge conjugation), $P$ (parity), and $T$ (time reversal) are known to be violated in nature, both singly and in pairs. Only the combination of the three - $CPT$ - appears to be an inversion symmetry transformation under which the laws of nature are strictly invariant. This fact has a very solid theoretical ground in the famous $CPT$ theorem[1–4], which ensures that exact $CPT$ invariance holds for any quantum field theory formulated on flat space-time assuming (1) Lorentz invariance, (2) Locality, and (3) Hermiticity.

Testing the validity of $CPT$ invariance therefore probes the most fundamental assumptions of our present understanding of particles and their interactions.

A violation of the $CPT$ 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 particular, in the last decade, in several attempts to discuss quantum gravity scenarios, speculative theoretical models have been considered which may exhibit a $CPT$-symmetry breakdown[5,6].

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 $\Delta m \approx 5 \times 10^9$ s$^{-1}$ ($\approx 3 \times 10^{-15}$ 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 $K_S$ (i.e. $\Delta m \approx 2\Delta\Gamma \simeq 2\Gamma_S$) makes possible to observe 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[7]. For instance a possible violation of the $CPT$ symmetry could manifest in conjunction with tiny modifications of the initial correlation, decoherence effects, or Lorentz symmetry violations, which, in turn, might be justified in a quantum theory of gravity. What makes the entangled $\mathrm{K}^0\bar{\mathrm{K}}^0$ pair a really unique system, even with respect to other similar neutral meson systems ($B_d^0$, $B_s^0$, and $D^0$), is the presence of peculiar 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's scale region, i.e. $\mathcal{O}(m_K^2/M_{Planck}) \sim 2 \times 10^{-20}$ GeV, which is a very remarkable level of accuracy.

## 2. "Standard" *CPT* Test From Unitarity

The complex parameter $\delta$ describes $CPT$ violation in $\mathrm{K}^0 - \bar{\mathrm{K}}^0$ mixing, and is proportional to the particle anti-particle masses and widths difference:

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

The real part of $\delta$ has been measured by the CPLEAR collaboration[8] studying the time behaviour of semileptonic decays from initially tagged $\mathrm{K}^0$ and $\bar{\mathrm{K}}^0$ mesons, while the imaginary part can be bounded imposing the unitarity condition[9–11].

The limits on $\Im\delta$ and $\Re\delta$ can be used to constrain the mass and width difference between $\mathrm{K}^0$ and $\bar{\mathrm{K}}^0$. In the limit $\Gamma_{\mathrm{K}^0} - \Gamma_{\bar{\mathrm{K}}^0} = 0$, i.e. neglecting $CPT$-violating effects in the decay amplitudes, eq.(1) translates into the best bound on the particle anti-particle fractional mass difference:

$$|m_{\mathrm{K}^0} - m_{\bar{\mathrm{K}}^0}| < 4.0 \times 10^{-19} \text{ GeV} \quad \text{at } 95 \text{ \% CL} \ .$$

It's 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 $\mathrm{K_S}$ and $\mathrm{K_L}$.

## 3. Search for Decoherence and *CPT* Violation Effects

DA$\Phi$NE, the Frascati $\phi$-factory is an $e^+e^-$ collider working at a center of mass energy of $\sqrt{s} \sim 1020$ MeV, corresponding to the peak of the $\phi$ resonance. The $\phi$-meson production cross section is $\sim 3\mu$b, and its decay into $\mathrm{K}^0\bar{\mathrm{K}}^0$ has a branching fraction of 34%, yielding $\sim 10^6$ $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs per pb$^{-1}$ of integrated luminosity. The neutral kaon pair is produced in a coherent quantum state with quantum numbers $J^{PC} = 1^{--}$:

$$|i\rangle = \frac{1}{\sqrt{2}}\{|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle - |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle\} = \frac{N}{\sqrt{2}}\{|\mathrm{K_S}\rangle|\mathrm{K_L}\rangle - |\mathrm{K_L}\rangle|\mathrm{K_S}\rangle\} \tag{2}$$

where $N \simeq 1$ is a normalization factor.

The KLOE experiment at DAΦNE completed its first data taking campaign in March 2006 with a total integrated luminosity of $\sim 2.5$ fb$^{-1}$, corresponding to a production of $\sim 7.5 \times 10^9$ $\phi$-mesons and $\sim 2.5 \times 10^9$ $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs.

The quantum interference between the two kaons initially in the entangled state in eq.(2) and decaying in the $CP$ violating channel $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^+\pi^-$, has been observed for the first time by the KLOE collaboration[12,13]. The measured $\Delta t$ distribution, with $\Delta t$ the absolute value of the time difference of the two $\pi^+\pi^-$ decays, can be fitted with the distribution:

$$I(\Delta t) \propto e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL})e^{-\frac{(\Gamma_S+\Gamma_L)}{2}\Delta t}\cos(\Delta m \Delta t)\ , \tag{3}$$

where the quantum mechanical expression in the $\{\mathrm{K_S}, \mathrm{K_L}\}$ basis has been modified with the introduction of a decoherence parameter $\zeta_{SL}$, and a factor $(1-\zeta_{SL})$ multiplying the interference term. Analogously, a $\zeta_{0\bar{0}}$ parameter can be defined in the $\{\mathrm{K}^0, \bar{\mathrm{K}}^0\}$ basis[14]. The results are[13]:

$$\begin{aligned} \zeta_{SL} &= (0.3 \pm 1.8_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}}) \times 10^{-2} \\ \zeta_{0\bar{0}} &= (1.4 \pm 9.5_{\mathrm{stat}} \pm 3.8_{\mathrm{syst}}) \times 10^{-7}\ , \end{aligned} \tag{4}$$

compatible with the prediction of quantum mechanics, i.e. $\zeta_{SL} = \zeta_{0\bar{0}} = 0$, and no decoherence effect. In particular the result on $\zeta_{0\bar{0}}$ has a high precision, $\mathcal{O}(10^{-6})$, the best in this kind of tests for an entangled system, due to the $CP$ suppression present in this specific decay channel, which naturally amplifies the sensitivity of any possible decoherence effect.

At a microscopic level, in a quantum gravity picture, space-time might be subjected to inherent non-trivial quantum metric and topology fluctuations at the Planck scale ($\sim 10^{-33}$ cm), called generically *space-time foam*, with associated microscopic event horizons. This space-time structure would lead to pure states evolving to mixed states, i.e. the decoherence of apparently isolated matter systems[15]. This decoherence, in turn, necessarily implies, by means of a theorem[16], $CPT$ violation, in the sense that the quantum mechanical operator generating $CPT$ transformations cannot be consistently defined.

A model for decoherence can be formulated[17–19] in which a single kaon is 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 $CPT$ violation. It has mass units and is presumed to be at most of $\mathcal{O}(m_K^2/M_{Planck}) \sim 2 \times 10^{-20}$ GeV.

The study of the same $I(\Delta t)$ distribution as in the $\zeta$ parameters analysis above, in the simplifying hypothesis of complete positivity, obtained the following result[13]:

$$\gamma = \left(0.7 \pm 1.2_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}\right) \times 10^{-21}\,\mathrm{GeV}\ , \tag{5}$$

compatible with no $CPT$ violation, while the sensitivity very interestingly surpasses the level of $\mathcal{O}(10^{-20}\,\mathrm{GeV})$.

As discussed above, in a quantum gravity framework inducing decoherence, the $CPT$ operator is *ill-defined*. This consideration might have intriguing consequences in correlated neutral kaon states, where the resulting loss of particle-antiparticle identity could induce a breakdown of the correlation in state (2) imposed by Bose statistics[20,21]. In this context the initial state (2) can be parametrized in general as:

$$|i\rangle = \frac{1}{\sqrt{2}}[|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle - |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle + \omega\left(|\mathrm{K}^0\rangle|\bar{\mathrm{K}}^0\rangle + |\bar{\mathrm{K}}^0\rangle|\mathrm{K}^0\rangle\right)] , \tag{6}$$

where $\omega$ is a complex parameter describing this peculiar $CPT$ violation phenomenon. Its order of magnitude could be at most $|\omega| \sim \left[(m_K^2/M_{\mathrm{Planck}})/\Delta\Gamma\right]^{1/2} \sim 10^{-3}$. A similar analysis[13] performed on the same $I(\Delta t)$ distribution as before, including in the fit the modified initial state eq.(6), yields the first measurement of the complex parameter $\omega$:

$$\Re(\omega) = \left(-1.6^{+3.0}_{-2.1}{}_{\mathrm{stat}} \pm 0.4_{\mathrm{syst}}\right) \times 10^{-4}$$
$$\Im(\omega) = \left(-1.7^{+3.3}_{-3.0}{}_{\mathrm{stat}} \pm 1.2_{\mathrm{syst}}\right) \times 10^{-4} , \tag{7}$$

with $|\omega| < 1.0 \times 10^{-3}$ at 95% C.L. and an accuracy that also in this case already reaches the interesting Planck scale region.

## 4. CPT and Lorentz Symmetry Tests

In the case of a well defined $CPT$ operator not commuting with the effective Hamiltonian, a general theoretical possibility for $CPT$ violation is based on spontaneous breaking of Lorentz symmetry[22–24], which appears to be compatible with the basic tenets of quantum field theory and retains the property of gauge invariance and renormalizability (Standard Model Extensions - SME). In 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:

$$\delta \approx i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K (\Delta a_0 - \vec{\beta_K} \cdot \Delta\vec{a})/\Delta m \tag{8}$$

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

Using 1.7 $\mathrm{fb}^{-1}$ of data collected at KLOE and studying the interference pattern of the entangled neutral kaon pairs in the $\phi \to \mathrm{K}^0\bar{\mathrm{K}}^0 \to \pi^+\pi^-\pi^+\pi^-$ final state, as a function of sidereal time and particle direction in celestial coordinates, the following results have been obtained[25]:

$$\Delta a_0 = (-6.0 \pm 7.7_{stat} \pm 3.1_{syst}) \times 10^{-18}\ \mathrm{GeV}$$
$$\Delta a_x = (\ \ 0.9 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-18}\ \mathrm{GeV}$$
$$\Delta a_y = (-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18}\ \mathrm{GeV}$$
$$\Delta a_z = (\ \ 3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18}\ \mathrm{GeV} .$$

These results constitute the most sensitive measurements in the quark sector of SME, and can be compared to similar results obtained in the B and D meson systems, where an accuracy of $\mathcal{O}(10^{-13}\text{GeV})$ has been reached[26].

## 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[27]. The appropriate preparation and detection of *in* and *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 only. The test can be easily implemented at KLOE and KLOE-2. Using this method it would be possible for the first time to directly test the $CPT$ symmetry in transition processes between meson states, rather than comparing masses, lifetimes, or other intrinsic properties of particle and anti-particle states, shedding light on possible new $CPT$ violating mechanisms, or further improving the precision of the present experimental limits.

## 6. Conclusions and Perspectives

The neutral kaon system constitutes a fantastic and unique laboratory for the study of the $CPT$ symmetry and the basic principles of quantum mechanics. The parameters related to several possible $CPT$ violations effects, including decoherence and Lorentz symmetry breaking effects which might be justified in a quantum gravity framework, have been measured in some cases with a precision that very interestingly reaches the Planck scale region.

A $\phi$-factory represents a unique opportunity to push forward these studies. It is also an ideal place to investigate the entanglement and correlation properties of the produced $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs. The KLOE physics program is continued by the KLOE-2 experiment, presently taking data at the DAΦNE facility with an upgraded detector[28]. Significant improvements are expected in almost all present $CPT$ tests, while the test based on the comparison of transition probabilities[27] will be implemented for the first time.

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