CPT and QM tests using kaon interferometry

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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 (in any order) | appears to be an exact symmetry of nature.

A rigorous proof of the CPT theorem can be found in Refs. [3, 4, 5] (see also Refs. [6, 7, 8] for some recent developments); it ensures that exact CPT invariance holds for any quantum field theory assuming (1) Lorentz invariance, (2) Locality, and (3) Unitarity (i.e. conservation of probability). Testing the validity of CPT invariance therefore probes the most fundamental assumptions of our present understanding of particles and their interactions.

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 $m \lesssim 10^{10}$ s$^{-1}$, where $m$ is the small mass difference between the exponentially decaying states $K_L$ and $K_S$. The fortunate coincidence that $m$ is about half the decay width of $K_S$ makes it possible to observe a variety of intricate interference phenomena in the production and decay of neutral kaons. In turn, such observations enable us to test quantum mechanics, the interplay of different conservation laws and the validity of various symmetry principles. In particular, the extreme sensitivity of the neutral kaon system to a variety of CPT-violating effects makes it one of the best candidates for an accurate experimental test of this symmetry [3]. As a guide for exit, the fractional mass difference $(m_{K_L} - m_{K_S}) = m_K$ can be considered; it can be measured at the level of $10^{-12}$ for neutral kaons, while, for pion parison, a limit of $10^{-14}$ can be reached on the corresponding quantity for the $B^0$ - $B^\ast_0$ system, and only of $10^{-5}$ for proton-antiproton [3].

2. CPT test from unitarity

The real part of the complex parameter $\lambda$, describing CPT violation in $K^0 - \bar{K}^0$ mixing, has been measured by the CLEO collaboration studying the time behaviour of semileptonic decays from initially tagged $K^0$ and $K^0$ mesons [13]:

$$\langle \lambda \rangle = (0.30 \pm 0.33\text{ stat} \pm 0.6\text{ syst}) \times 10^{-3}$$  \hspace{1cm} (1)

One of the most precise and significant tests of the CPT symmetry comes from the unitarity relation, originally derived by Bell and Steinberger [11]:

$$\begin{align*}
&\frac{s}{s} + \frac{L}{L} + \frac{1}{X} \tan \frac{SW}{\lambda} \leq \frac{1}{L} \mp 3 \frac{X}{s} \lambda \leq \frac{1}{X} \tan \frac{SW}{\lambda} \\
&\frac{1}{s} \frac{L}{L} \frac{1}{X} \lambda \leq \frac{1}{X} \tan \frac{SW}{\lambda} \frac{f}{f} \lambda \leq \frac{1}{X} \tan \frac{SW}{\lambda} \frac{f}{f}
\end{align*}$$  \hspace{1cm} (2)

where $s$ is the usual complex parameter describing CPT violation in $K^0 - \bar{K}^0$ mixing; $s$ and $L$ are the widths of the physical states $K_S$ and $K_L$; $SW$ is the superweak phase; $\lambda$ is the decay amplitude of the state $K_L$ into a final state $f$, and the sum runs over all possible final states. The above relationship can be used to bound the parameter $\lambda$, after having provided all the input parameters, $s$, $L$, and $SW$ as inputs. Using several measurement results from the KLOE experiment [12], values from the Particle Data Group (PDG), and a combination of KLOE and CLEO data, the following result is obtained [3]:

$$\langle \lambda \rangle = (0.30 \pm 1.2) \times 10^{-3}$$  \hspace{1cm} (3)

which is the most stringent limit on $\lambda$; the main limiting factor of this result being the uncertainty on the phase $\lambda$, entering in the parameter $\lambda$.

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1 The result $\langle \lambda \rangle = (161 \pm 85) \times 10^{-3}$, which is obtained in the same analysis, is not relevant for the discussion here.
The kaon pair is produced in a coherent quantum state

\[ \text{jet} \leq m_K < 5.1 \times 10^{19} \text{ GeV at } 95\% \text{ CL.} \]

A preliminary update including the latest results on

+ by the KTeV collaboration \[ \text{KTeV} \] yields slightly improved results \[ \text{KTeV} \] :

\[ \text{jet} \leq m_K < 4.0 \times 10^{19} \text{ GeV at } 95\% \text{ CL.} \]

### 3. CPT and QM tests

DA NE, the Frascati factory, is an e⁺e⁻ collider working at a center of mass energy of \( \sqrt{s} = 1020 \text{ MeV} \), corresponding to the peak of the resonance. The production cross section is \( 3 \text{ b} \), and its decay into \( K^0 \bar{K}^0 \) has a branching fraction of \( 34\% \). The neutral kaon pair is produced in a coherent quantum state with quantum numbers \( J^P = 1^- \):

\[ \text{jet} \leq m_K < 5.1 \times 10^{19} \text{ GeV at } 95\% \text{ CL.} \]

\[ \text{jet} \leq m_K < 4.0 \times 10^{19} \text{ GeV at } 95\% \text{ CL.} \]

where the quantum mechanical expression in the \( f_{K^0}K_{L^0} \) basis has been modified with the introduction of a decoherence parameter \( \mathcal{S}_L \) and a factor \( (1 - \mathcal{S}_L) \) multiplying the interference term. Analogously, a \( 0^0 \) parameter can be defined in the \( K^0 \bar{K}^0 \) basis. A fit having included resolution and detection efficiency effects, having taken into account the background due to coherent and incoherent \( K \) regeneration on the beam pipe wall, the small contamination of non-resonant \( e^+e^- \) events, and keeping \( m, s, l \) fixed at the PDG values, the fit is performed on the distribution. The analysis of a data sample corresponding to \( L = 380 \text{ pb}^{-1} \) yields the following results \[ \text{KLOE} \] :

\[ s_L = 0.018 \quad 0.040_{\text{stat}} \quad 0.007_{\text{sys}} \]

\[ 0.0 = (1.0 \quad 2.1_{\text{stat}} \quad 0.4_{\text{sys}}) \times 10^6 ; \quad (6) \]

comparable with the prediction of quantum mechanics, i.e. \( s_L = 0.00 \), and no decoherence effect. In particular the result on \( s_L \) has a high precision, \( O(10^6) \), due to the CP suppression present in the specific decay channel; it is an improvement by two orders of magnitude over the previous limit, obtained by Bertlman and co-workers \[ \text{KLOE} \] in a re-analysis of CPLEAR data. This result can also be compared to a similar one recently obtained in the \( B \) meson system \[ \text{CLEO} \], where an accuracy of \( O(10^8) \) has been reached.

At a microscopic level, in a quantum gravity picture, space-time is assumed to depend on non-trivial quantum metric and topology fluctuations at the Planck scale \( (10^{33} \text{ cm}) \), 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 \[ \text{KLOE} \]. This decoherence, in turn, necessarily implies, by means of a theorem \[ \text{KLOE} \] , CPT violation, in the sense that the quantum mechanical operator generating CPT transformations cannot be consistently de ned.

A model for decoherence can be formulated \[ \text{KLOE} \] in which a single kaon is described by a density matrix that obeys a modified Liouville-von Neumann equation:

\[ \frac{d}{dt} \rho = \mathcal{H} \rho + \gamma \mathcal{P} \mathcal{O} \mathcal{O} \mathcal{P} \rho \quad \gamma > 0 \]

where \( \mathcal{H} \) is the neutral kaon state vector Hamiltonian, and the extra term \( \mathcal{O} \) would induce decoherence in the system, and depends on three real parameters, \( \mathcal{S}_L \) which violates CPT symmetry and quantum mechanics (they satisfy the inequalities \( \gamma > 0 \) and \( \mathcal{S}_L > 0 \)).
The CPLEAR collaboration, studying the time-behaviour of single neutral kaon decays to $^{*}$ and final states, obtained the following results:\(^2\):\(^3\),

\[
\begin{align*}
\Delta m &\approx (0.5 \pm 2.8) \times 10^{-17} \text{ GeV} \\
\Delta m &\approx (2.5 \pm 2.3) \times 10^{-19} \text{ GeV} \\
&\approx (1 \pm 2.5) \times 10^{-21} \text{ GeV}.
\end{align*}
\]

The KLOE collaboration, studying the same I($^*$; $^*$; t) distribution as in the parameters analysis, in the simplifying hypothesis of complete positivity\(^2\), i.e. $\lambda = 0$ and $\lambda = 0$, obtained the following result\(^3\):

\[
\begin{align*}
\Delta m &\approx 13^{+2.8}_{-2.4} \text{ stat} \times 0 \times \text{syst} \times 10^{-21} \text{ GeV}.
\end{align*}
\]

All results are compatible with no CPT violation, while the sensitivity approaches the interesting level of $0(10^{-20} \text{ GeV})$.

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 (3) imposed by Bose statistics\(^2\).\(^2\). A similar initial state (4) can be parametrized in general as:

\[
\begin{align*}
\Psi &\approx (K^0 i K^0 i K^0 i K^0 i + K^0 i K^0 i K^0 i K^0 i); \quad (10)
\end{align*}
\]

where $\lambda$ is a complex parameter describing a completely novel CPT violation phenomenon, not included in previous analyses. Its order of magnitude could be at most

\[
\begin{align*}
\lambda &\approx (m_{\text{Planck}}/M)(1-2) \times 10^{-3},
\end{align*}
\]

with $\lambda = \lambda_{\Sigma}$. A similar analysis performed by the KLOE collaboration on the same I($^*$; $^*$; t) distribution as before, including in the t the modified initial state eq.(10), yields the result measure of the complex parameter $\lambda$\(^1\):

\[
\begin{align*}
<() &\approx 13^{+2.8}_{-2.4} \text{ stat} \times 0 \times \text{syst} \times 10^{-4}, \\
<() &\approx 3^{+4.8}_{-2.4} \text{ stat} \times 0 \times \text{syst} \times 10^{-4}.
\end{align*}
\]

with an accuracy that already reaches the interesting Planck scale region.

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\(^2\)This hypothesis, reducing the number of free parameters, makes the t of the experimental distribution easier, even though it is not strictly necessary.

A preliminary analysis of a KLOE data sample corresponding to $\sim 1 \text{ fb}^{-1}$ yields the following updated results\(^3\):

\[
\begin{align*}
\Delta m &\approx 0.009 \pm 0.022 \text{ stat}, \\
&\approx 0.003 \pm 0.012 \text{ stat} \times 10^{-6}, \\
&\approx 0.8^{+1.5}_{-1.2} \text{ stat} \times 10^{-21} \text{ GeV}, \\
&\approx 2.5^{+2.3}_{-2.3} \text{ stat} \times 10^{-4}, \\
&\approx 2.9^{+3.4}_{-3.1} \text{ stat} \times 10^{-4}.
\end{align*}
\]

while the analysis of the full KLOE data sample is being completed.

4. CPT violation and Lorentz symmetry breaking

CPT invariance holds for any realistic Lorentz-invariant quantum field theory. However, a very general theoretical possibility for CPT violation is based on spontaneous breaking of Lorentz symmetry\(^2\),\(^3\),\(^4\), 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 itself as an order parameter in the parameter $\lambda$, and exhibits a dependence on the $4\pi$ on the entum of the kaon:

\[
is = \sin \left( \frac{\pi}{2} \right), \quad \lambda (a_0, \lambda_0, \lambda) = m \quad (12)
\]

where $a$ and $\lambda_0$ are the kaon boost factor and velocity in the observer frame, and $a$ are four CPT- and Lorentz-violating coefficients for the two valence quarks in the kaon.

Following Ref.\(^3\), the time dependence arising from the rotation of the Earth can be explicitly displayed in eq.\(^1\) by choosing a three-dimensional basis ($x^0, y^0, z^0$) in the rotating frame $\hat{e}$, with the $Z$ axis along the Earth’s rotation axis, and a basis ($k^0, y^0, z^0$) for the rotating (laboratory) frame $\hat{e}$. The CPT violating parameter \( \Delta m \) may then be expressed as:

\[
\begin{align*}
\Delta m &\approx \frac{1}{2} Z^2 \left( p; \eta_{\text{tid}} \right) \\
&\approx \frac{i \sin \left( \frac{\pi}{2} \right)}{m} \left( a_0 + a \right),
\end{align*}
\]

where $t_{\text{tid}}$ is the sidereal time, $\Omega$ is the Earth’s sidereal frequency, $\cos = \Omega^2 Z^2$, and $a$ are the conventional polar and azimuthal angles defined in the laboratory frame about the $Z$ axis, and an integration on the azimuthal angle $\lambda$ has been performed.
assum ing a symmetric decay distribution in this variable\(^3\). The sensitivity to the four \( a \) parameters can be very different for fixed target and collider experiments, showing complementary features [30].

At KLOE the \( a_0 \) parameter can be evaluated through the difference of the semileptonic charge asymmetries:

\[
A_{SL} = \frac{(K_{SL} \uparrow ! \uparrow I') (K_{SL} \uparrow + l)}{(K_{SL} \uparrow ! \uparrow I') + (K_{SL} \uparrow + l)};
\]

by performing the measurement of each asymmetry with a symmetric integration over the polar angle, thus averaging to zero any possible contribution from the term's proportional to \( \cos \theta \) in eq. (13):

\[
A_S \cdot A_L \cdot 4<\sin \theta_s \cdot e^{i \psi_s} > \cdot \frac{m}{k} \cdot a_0 = (14)
\]

In this way a first preliminary evaluation of the \( a_0 \) parameter can be obtained by KLOE [33,34]:

\[
a_0 = (0.4 \pm 1.8) \times 10^{-17} \text{ GeV} \quad (15)
\]

With the analysis of the full KLOE data sample \((L = 2.5 \text{ fb}^{-1})\) an accuracy \((a_0) \times 10^{-18} \text{ GeV} \) could be reached.

At KLOE the \( a_{XPQ} \) parameters can be evaluated performing a sidereal time dependent analysis of the asymmetry:

\[
A(t) = \frac{N^+ N}{N^+ N + N^-} \quad ;
\]

with

\[
N^+ = I^+ \quad (t>0) \quad ; \quad N^- = I^- \quad (t<0) \quad ;
\]

where the two identical 
\( P \) states are distinguished by their emission in the forward \((\cos \theta > 0)\) or backward \((\cos \theta < 0)\) hemispheres (denoted by the symbol + and −, respectively), and \( t \) is the time difference between \((+) \) and \((-) \) decays. A preliminary analysis based on a data sample corresponding to an integrated luminosity \(L = 1 \text{ fb}^{-1}\) yields the following results [33,34]:

\[
\begin{align*}
a_x &= (6.3 \pm 0.2) \times 10^{-18} \text{ GeV} \\
a_y &= (2.8 \pm 0.2) \times 10^{-18} \text{ GeV} \\
a_z &= (2.4 \pm 0.7) \times 10^{-18} \text{ GeV}.
\end{align*}
\]

A preliminary measurement performed by the KTeV collaboration [34] based on the search for sidereal time variation of the phase, constrains \( a_x \) and \( a_y \) to less than \(9 \times 10^{-22} \text{ GeV} \) at 90\% C.L.

These results can also be compared to similar ones recently obtained in the B meson system [35], where an accuracy on the \( a_0 \) parameter of \(10^{-13} \text{ GeV} \) has been reached.

5. Future plans

A proposal [36,37] has been presented for a physics program to be carried out with an upgraded KLOE detector, KLOE-2, at an upgraded DA NE machine, which is expected to deliver an integrated luminosity up to \(20 \text{ pb}^{-1}\). The major upgrade of the KLOE detector would consist in the addition of an inner tracker for the improvement of decay vertex resolution, therefore in proving the sensitivity on several parameters based on kaon interferometry measurements. The KLOE-2 program concerning neutral kaon interferometry is summarized in Table I, where the KLOE-2 statistical sensitivities on the main parameters that can be extracted from kaon decay time distributions \(I(f_1; f_2; t)\) with different choices of final states \(f_1\) and \(f_2\) are listed for an assumed integrated luminosity \(L = 50 \text{ fb}^{-1}\), and compared to the best presently published measurements.

6. Conclusions

The neutral kaon system constitutes an excellent laboratory for the study of the CPT symmetry and the basic principles of quantum mechanics. Several parameters related to possible CPT violations, including decoherence and Lorentz symmetry breaking effects, have been measured in some cases with a precision reaching the interesting Planck scale region. Simple quantum coherence tests have been also performed. All results are consistent with no violation of the CPT symmetry and/or quantum mechanics.

A 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 \(K_0 \bar{K}_0\) pairs. A proposal for continuing the KLOE physics program (KLOE-2) at an improved DA NE machine, able to deliver an integrated luminosity up to \(20 \text{ pb}^{-1}\), has been recently presented. In proven cases by about one order of magnitude in almost all present limits are expected.

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Table I KLOE-2 statistical sensitivities on several parameters.

| $f_1$ | $f_2$ | Parameter | Best published meas. | KLOE-2 (50 fb$^{-1}$) |
|-------|-------|-----------|----------------------|-----------------------|
| K $\pi$ e | 1 | $A_\pi$ | (15 11) 10$^{-3}$ | 1 10$^{-3}$ |
|       | 0 0 | $A_\gamma$ | (3322 58 47) 10$^{-6}$ | 25 10$^{-6}$ |
|       | 0 0 | $A_\mu$ | (12 2.3) 10$^{-3}$ (PDG) | 3 10$^{-3}$ |
| $^{1}$ | + | $<(+<x)$ | = (0.25 0.23) 10$^{-3}$ (PDG) | 0.2 10$^{-3}$ |
| $^{1}$ | + | < | = (0.25 0.23) 10$^{-3}$ (PDG) | 0.2 10$^{-3}$ |
|       | + | $= + = x$ | = - (0.05 1.2) 10$^{-3}$ (PDG) | 3 10$^{-3}$ |
|       | + | m | 5288 ± 0.43 10$^{-3}$ s$^{-1}$ | 0.3 10$^{-3}$ s$^{-1}$ |
|       | + | s$_L$ | (18 41) 10$^{-3}$ | 0.2 10$^{-3}$ |
|       | + | s$_0$ | (13 2.1) 10$^{-6}$ | 3 10$^{-6}$ |
|       | + | (0.5 28) 10$^{-17}$ GeV | 2 10$^{-17}$ GeV |
|       | + | (+2.5 2.3) 10$^{-19}$ GeV | 0.2 10$^{-19}$ GeV |
|       | + | (+1.1 2.5) 10$^{-21}$ GeV | 0.2 10$^{-21}$ GeV |
|       | + | $< !$ | (1.1$^{+0.27}_{-0.10}$ 0.9) 10$^{-4}$ | 2 10$^{-5}$ |
|       | + | $< !$ | (3.8$^{+4.3}_{-0.5}$ 0.6) 10$^{-4}$ | 2 10$^{-5}$ |
| $K_{ZLe}$ e | a$_0$ | (prelim.: (0.4 1.8) 10$^{-18}$ GeV) | 2 10$^{-18}$ GeV |
|       | a$_2$ | (prelim.: (2.4 9.7) 10$^{-18}$ GeV) | 7 10$^{-18}$ GeV |
|       | $a_\chi$, $a_\gamma$ | (prelim. < 9.2 10$^{-22}$ GeV) | 4 10$^{-19}$ GeV |

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