CPT and Quantum Mechanics Tests with Kaons: Theory

Nick E. Mavromatos[a]

[a]King's College London, Department of Physics, Strand, London WC2R 2LS, United Kingdom

In this brief review talk I first discuss some theoretical motivations for potential CPT Violation and deviations from ordinary quantum mechanical behavior of field theoretic systems in the background of some quantum gravity models. Then I proceed to a description of precision tests of CPT symmetry using neutral and charged Kaons. I emphasize the possibly unique rôle of neutral meson factories in providing specific tests of models in which the CPT quantum mechanical operator is not well defined, leading to modifications of Einstein-Podolsky-Rosen (EPR) particle correlators.

1. CPT symmetry and Quantum Gravity

Any quantum theory, formulated on flat space times, is symmetric under the combined action of CPT transformations, provided the theory respects (i) Locality, (ii) Unitarity (i.e. conservation of probability) and (iii) Lorentz invariance. This is the famous CPT theorem [1]. An extension of this theorem to quantum gravity is by no means an obvious one; there may be information loss, in certain space-time foam backgrounds [2], implying an evolution from pure to mixed quantum states, and hence decoherence [2,3]. In such situations *particle phenomenology* has to be reformulated [3,4] by viewing our low-energy world as an open quantum system.

In such cases the $ matrix is *not invertible*, and this implies [5] that the CPT operator itself is *not well defined*, at least from an effective field theory point of view. This is a strong form of CPT violation. This form of CPT Violation (CPTV) introduces a fundamental arrow of time/microscopic time irreversibility, unrelated in principle to CP properties. Within the scope of the present talk I will restrict myself to decoherence and CPT invariance tests within neutral Kaons [3,6–8]. As I will argue later on, this type of (decoherence-induced) CPT Violation (CPTV) exhibits some fairly unique effects in ϕ (B-meson, ...) factories [9], associated with a potential modification of the Einstein-Podolsky-Rosen (EPR) correlations of the entangled neutral Kaon (B-meson, ...) states produced after the decay of the ϕ-(or Υ-, ...) meson.

Another fundamental reason for CPT violation (CPTV) in quantum gravity is *spontaneous breaking of Lorentz symmetry (SBL)* [10], without necessarily implying decoherence. In this case the ground state of the field theoretic system is characterized by non trivial vacuum expectation values of certain tensorial quantities, $\langle \mathcal{A}_\mu \rangle \neq 0$, or $\langle \mathcal{B}_{\mu_1\mu_2\ldots} \rangle \neq 0$. In this talk I will restrict myself to Lorentz tests using neutral Kaons [10].

I must stress at this point that QG-decoherence and Lorentz Violation (LV) are in principle independent [4]. The important difference of CPT violation in SBL models of quantum gravity from that in space-time foam situations lies on the fact that in the former case the CPT operator is well defined, but it *does not commute* with the effective Hamiltonian of the matter system. In such cases one may parametrize the Lorentz and/or CPT breaking terms by local field theory operators in the effective lagrangian, leading to a construction known as the "standard model extension" (SME) [10], which is a framework to study precision tests of such effects.

In certain circumstances one may also violate locality, but I will not discuss this case explicitly here. Of course violations of locality could also be tested with high precision by means of a study of discrete symmetries in meson systems.

I must stress that the phenomenology of CPT violation is complicated, and there seems *not* to be a *single* figure of merit for it. Depending on the precise way by which CPT violation is realized in a given class of models of QG, there are different ways by which we can test the violation [4]. I stress that within the above frameworks, CPT violation does *not necessarily* imply mass differences between particles and antiparticles.

2. Lorentz Violation and Neutral Kaons

I commence my discussion by a very brief description of experimental tests of Lorentz symmetry, within the SME framework, using neutral Kaons, both single [10] and entangled states in a ϕ factory [11]. In order to isolate the terms in SME effective Hamiltonian that are pertinent to neutral Kaon tests, one should notice [10] that the relevant CPTV and LV parameter δ_K must be flavour diagonal, C violating but P,T preserving, as a consequence of strong interaction properties in neutral meson evolution. This implies that δ_K is sensitive only to the $-a^q_\mu \overline{q}\gamma_\mu q$ quark terms in SME [10], where a_μ is a Lorentz and CPT violating parameter, with dimensions of energy, and q denote quark fields, with the meson composition being denoted by $M = q_1\overline{q}_2$.

The analysis of [10], then, leads to the following relation of the Lorentz and CPT violating parameter a_μ to the CPT violating parameter δ_K of the neutral Kaon system: $\delta_K \simeq i \sin\widehat{\phi} \exp(i\widehat{\phi})\gamma \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right)/\Delta m$, with the short-hand notation S=short-lived, L=long-lived, $\Delta m = m_L - m_S$, $\Delta\Gamma = \Gamma_S - \Gamma_L$, $\widehat{\phi} = \arctan(2\Delta m/\Delta\Gamma)$, $\Delta a_\mu \equiv a^{q_2}_\mu - a^{q_1}_\mu$, and $\beta^\mu_K = \gamma(1, \vec{\beta}_K)$ the 4-velocity of the boosted kaon. The experimental bounds of a_μ in neutral-Kaon experiments are based on searches of sidereal variations of δ_K (day-night effects). From KTeV experiment [12] the following bounds of the X and Y components of the a_μ parameter have been obtained $\Delta a_X, \Delta a_Y < 9.2 \times 10^{-22}$ GeV, where X, Y, Z denote sidereal coordinates. Complementary measurements for the a_Z component can come from ϕ factories [11].

3. Quantum Gravity Decoherence and Neutral Kaons

QG may induce decoherence and oscillations $K^0 \leftrightarrow \overline{K}^0$ [3,6], thereby implying a two-level quantum mechanical system interacting with a QG "environment". Upon the general assumptions of average energy conservation and monotonic entropy increase, and the specific (to the Kaon system) assumption about the respect of the $\Delta S = \Delta Q$ rule by the QG medium, the modified evolution equation for the respective density matrices of neutral Kaon matter reads [3]:

$$\partial_t \rho = i[\rho, H] + \delta\not{H}\rho \ ,$$

where H denotes the hamiltonian of the Kaon system, that may contain (possible) CPTV differences of masses and widths between particles and antiparticles [6], and the decoherence matrix $\delta\not{H}$ is given by [3]:

$$\delta\not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix} .$$

Positivity of ρ requires: $\alpha, \gamma > 0, \quad \alpha\gamma > \beta^2$. Notice that α, β, γ violate *both* CPT, due to their decohering nature [5], and CP symmetry, as they do not commute with the CP operator $\widehat{CP}$ [6]: $\widehat{CP} = \sigma_3 \cos\theta + \sigma_2 \sin\theta, \qquad [\delta\not{H}_{\alpha\beta}, \widehat{CP}] \neq 0$. As pointed out in [8], however, in the case of ϕ-factories complete positivity is guaranteed within the above (single-particle) framework only if the further conditions $\alpha = \gamma$ and $\beta = 0$ are imposed. Experimentally the complete positivity hypothesis, and thus the above framework, can be tested explicitly by keeping all three parameters. In what follows, as far as single Kaon states are concerned, we shall keep the α, β, γ parametrization [6], and give the available experimental bounds for these parameters. The relevant observables are defined as $\langle O_i \rangle = \mathrm{Tr}\,[O_i \rho]$. For neutral kaons, one looks at decay asymmetries [6] (c.f. fig. 1 for the case of 2π final states). The important point to notice is that the two types of CPTV, within and outside quantum mechanics, can be *disentangled experimentally* [6].

We next mention that, typically, for instance when the final states are 2π, one has a time evolution of the decay rate $R_{2\pi}$: $R_{2\pi}(t) = c_S\, e^{-\Gamma_S t} + c_L\, e^{-\Gamma_L t} + 2c_I\, e^{-\Gamma t}\cos(\Delta m t - \phi)$, where S=short-lived, L=long-lived, I=interference term, $\Delta m = m_L - m_S$, $\Delta\Gamma = \Gamma_S - \Gamma_L$, $\Gamma = \frac{1}{2}(\Gamma_S + \Gamma_L)$.

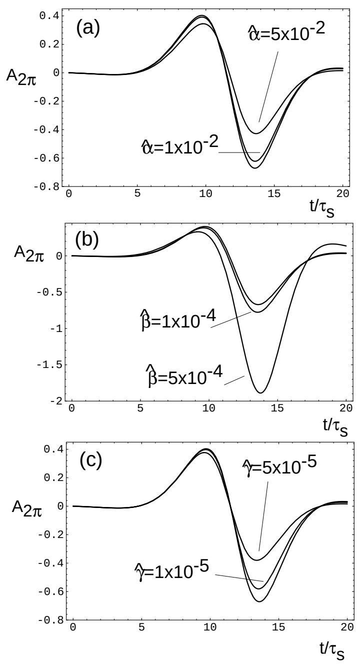

Figure 1. Typical neutral kaon decay asymmetries $A_{2\pi}$ [6] indicating the effects of quantum-gravity induced decoherence.

One may thus define the *Decoherence Parameter* $\zeta = 1 - \frac{c_I}{\sqrt{c_S c_L}}$, as a (phenomenological) measure of quantum decoherence induced in the system. In our decoherence scenario, ζ corresponds to a particular combination of the decoherence parameters [6] $\zeta \to \frac{\widehat{\gamma}}{2|\epsilon^2|} - 2\frac{\widehat{\beta}}{|\epsilon|}\sin\phi$, with the notation $\widehat{\gamma} = \gamma/\Delta\Gamma$, *etc.*

The CPLEAR measurements gave the following bounds [13] $\alpha < 4.0 \times 10^{-17}$ GeV , $|\beta| < 2.3. \times 10^{-19}$ GeV , $\gamma < 3.7 \times 10^{-21}$ GeV, which are not much different from theoretically expected values in some optimistic scenarios [6] α , β , $\gamma = O(\xi \frac{E^2}{M_P})$. The experiment KLOE at DAΦNE updated these limits recently by measuring for the first time the γ parameter for entangled Kaon states [11,14]: $\gamma_{\rm KLOE} = (1.1^{+2.9}_{-2.4} \pm 0.4) \times 10^{-21}$ GeV, as well as the (naive) decoherence parameter ζ. This bound can be improved by an order of magnitude in upgraded facilities, such as KLOE-2 at DAΦNE-2 [11].

4. CPTV and Modified EPR Correlations of Entangled Neutral Kaon States

If CPT is *intrinsically* violated, in the sense of being not well defined due to decoherence [5], the Neutral mesons K^0 and $\overline{K}^0$ should *no longer* be treated as *identical particles.* As a consequence [9], the initial entangled state in ϕ factories $|i>$, after the ϕ-meson decay, assumes the form:

$$|i> \;=\; \mathcal{N}\Big[\Big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\Big) + \omega\Big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\Big)\Big]$$

where $\omega = |\omega|e^{i\Omega}$ is a complex parameter, parametrizing the intrinsic CPTV modifications of the EPR correlations. The ω-parameter controls the amount of contamination of the final C(odd) state by the "wrong" (C(even)) symmetry state. The appropriate observable (c.f. fig. 2) is the "intensity" $I(\Delta t) = \int_{\Delta t \equiv |t_1 - t-2|}^{\infty} |A(X,Y)|^2$, with $A(X,Y)$ the appropriate ϕ decay amplitude [9], where one of the Kaon products decays to the final state X at t_1 and the other to the final state Y at time t_2 (with $t = 0$ the moment of the ϕ decay). The KLOE experiment has just released the first measurement of the ω parameter [11,14]: $\mathrm{Re}(\omega) = \big(1.1^{+8.7}_{-5.3} \pm 0.9\big) \times 10^{-4}$, $\mathrm{Im}(\omega) = \big(3.4^{+4.8}_{-5.0} \pm 0.6\big) \times 10^{-4}$. At least an order of magnitude improvement is expected for upgraded facilities such as KLOE-2 at (the upgraded) DAΦNE-2 [11]. This sensitivity is not far from certain optimistic models of space time foam leading to ω-like effects [15].

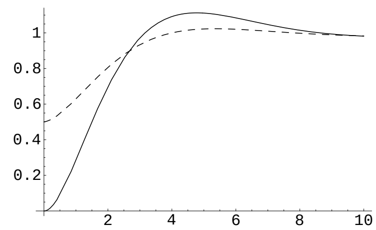

Figure 2. A characteristic case of the intensity $I(\Delta t)$, with $|\omega| = 0$ (solid line) vs $I(\Delta t)$ (dashed line) with $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} - 0.16\pi$, for definiteness [9].

We close this section by mentioning that the ω effect can be disentangled experimentally from *both*, the C(even) background - by means of different interference with the C(odd) resonant contributions, and the decoherent evolution ($\alpha = \gamma$) effects [9] - due to different structures.

5. Precision T, CP and CPT Tests with Charged Kaons

Precision tests of discrete symmetries can also be performed with charged Kaons, which is a case that generated a great interest in this conference [16], as a result of the (recently acquired) high statistics at the NA48 experiment [17], in certain decay channels, which allows for precision tests of the chiral perturbation theory [16]. For our purposes of testing CPT symmetry, we shall restrict ourselves to one particular charged Kaon decay, $K^\pm \to \pi^+ + \pi^- + \ell^\pm + \nu_\ell(\overline{\nu}_\ell)$, abbreviated as $K^\pm_{\ell 4}$. One can perform independent precision tests of T, CP and CPT using this reaction [18], by comparing the decay rates of the K^+ mode with the corresponding decays of the K^- mode, as well as tests of $\Delta S = \Delta Q$ and $|\Delta I| = 1/2$ isospin rules. If CPT is violated, through microscopic time irreversibility [5], then the phase space analysis for the products of the reaction, from which one obtains the di-pion strong-interaction phase shifts, needs to be modified [18].

I would like to finish this section by mentioning the possibility of exploiting the recently attained high statistics for charged Kaons in the NA48 experiment [17] so as to use appropriate combinations of *both* reaction modes $K^\pm_{\ell 4}$ for precision tests of physics beyond the Standard Model (SM), such as supersymmetry, *etc.*, including possible CPT violations. One could look at T-odd triple momentum correlators [19] $\vec{p}_\ell \cdot (\vec{p}_{\pi_1} \times \vec{p}_{\pi_2})$. The so constructed CP-violating observables are independent of the lepton polarization and thus easier to measure in a high statistics environment, such as the NA48 experiment [17].

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