NEW LIMITS ON CPT SYMMETRY VIOLATION IN CHARM MESONS*

Mateusz Kmieć, Wojciech Krzemień, Adam Szabelski
Wojciech Wiślicki

National Centre for Nuclear Research, Poland

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Small violations of CPT symmetry are permissible in several extensions of the Standard Model. Recently, we published new constraints on the CPT violation parameter z by reinterpreting the LHCb measurement of the time-dependent asymmetry in the Cabbibo-favoured $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^+\pi^-$ decays. The resulting limits are two orders of magnitude stricter than the previous leading result reported by the FOCUS Collaboration. In this contribution, we discuss the recent result, which is the tightest constraint on the CPTV in the charm sector to date. We also explore prospects for placing bounds on CPT violation in the Standard Model Extension framework.

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1. Introduction

The CPT symmetry refers to the invariance of physical laws under the combined transformations of charge conjugation (C), spatial inversion (P), and time reversal (T). It is one of the few fundamental symmetries strictly conserved in nature. The fundamental significance of the CPT symmetry is expressed through the *CPT theorem* which states that all quantum field theories (QFTs) based on a Hermitian, local, Lorentz-invariant, and normal-ordered Lagrangian must also be invariant under the transformation corresponding to the product of C, P, and T [1]. As a result, all QFTs describing fundamental particle interactions within the Standard Model (SM) must be CPT invariant.

The CPT symmetry is connected to the Poincaré invariance of QFTs in flat spacetime. However, when gravitational effects are present, global spacetime symmetries no longer hold in the same way, requiring a reconsideration of the relationship between CPT symmetry and Lorentz invariance.

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Consequently, some extensions of QFT, incorporating gravity or strings, will include violation of CPT at the scales of energy or space-time dimensions where quantum gravity is expected to be significant, *i.e.* close to the Planck scale [2–4].

At energies presently available at high-energy accelerators and cosmic rays, these effects are expected to be very small, and their observation poses an experimental challenge. However, the system of the neutral flavoured meson undergoing quantum oscillations (mixing) allows for this type of study. Such measurements have been performed so far, *cf.* Refs. [5–8], including the finding of the recently published study [9] discussed in this paper.

This paper also includes a discussion on the prospects regarding the studies of CPTV in the charm sector by using a model-independent framework based on the effective field theory, known as the Standard Model Extension (SME) [10, 11] and the LHCb data. In the SME, the Lagrangian density contains the CPT- and Lorentz-violating terms with coupling constants serving as control parameters contributing to several physical observables which values can be determined experimentally. Here, we restrict our attention to the CPTV parameters relevant for the studies of neutral D^0 mesons related to differences of couplings of quarks with the hypothetical Lorentz-violating field: Δa_X, Δa_Y, Δa_Z, Δa_0. The definitions of these parameters can be found in Ref. [11].

2. Neutral flavoured meson time evolution formalism

The neutral meson system is described by a linear combination of $|P^0\rangle$ and $|\bar{P}^0\rangle$ strong interaction eigenstates (flavour states). The state of the system can be represented by the ket $|\Psi(t)\rangle$ which satisfies the Schrödinger-type equation with a 2×2 effective Hamiltonian H^{eff} [11, 12]

$$i\hbar \frac{\mathrm{d}}{\mathrm{d}t} |\Psi(t)\rangle = H^{\text{eff}} |\Psi(t)\rangle \,. \tag{1}$$

In this formalism, the weak interactions are treated as a perturbation to the sum of the strong and electromagnetic parts of the Hamiltonian [1]. The diagonal elements of H^{eff} can be associated with the mass- and decay-width of the flavour states, m_{D^0} and Γ_{D^0}, respectively[1]

$$H^{\text{eff}} = \begin{pmatrix} m_{D^0} - \frac{i}{2}\Gamma_{D^0} & c_1 - \frac{i}{2}c_2 \\ c_1^* - \frac{i}{2}c_2^* & m_{\bar{D}^0} - \frac{i}{2}\Gamma_{\bar{D}^0} \end{pmatrix} . \tag{2}$$

[1] Parameters $c_{1,2}$ are complex numbers relative values of which are connected to T conservation.

In the alternative parameterization, the matrix elements are expressed in terms of complex parameters p, q, z [13]

$$H^{\mathrm{eff}} = \frac{1}{2}\Delta\lambda \begin{pmatrix} \frac{\lambda}{\Delta\lambda} + z & \sqrt{1-z^2}\frac{q}{p} \\ \sqrt{1-z^2}\frac{p}{q} & \frac{\lambda}{\Delta\lambda} - z \end{pmatrix} . \tag{3}$$

The parameter z is non-zero if and only if CPT is violated, whereas $|p/q| = 1$ if and only if T is conserved. By comparing the two parametrisations, z can be expressed in terms of $\delta m = m_{D^0} - m_{\bar{D}^0}$, $\delta\Gamma = \Gamma_{D^0} - \Gamma_{\bar{D}^0}$, and the mixing parameters x, y (see Refs. [9, 14])

$$z = \frac{\delta m - i\delta\Gamma/2}{\Gamma(x - iy)} . \tag{4}$$

3. Time-dependent asymmetries

It can be shown [11] that for studies of CPTV with the uncorrelated D^0 mesons decaying into the final state $f = K^-\pi^+$, the relevant observable is the time-dependent asymmetry, which can be constructed by combining the time-dependent decay probabilities in the following way:

$$A_{\mathrm{CPT}}(t) = \frac{\bar{P}_{\bar{f}}(t) - P_f(t)}{\bar{P}_{\bar{f}}(t) + P_f(t)} , \tag{5}$$

where the time-dependent decay probabilities can be calculated as $P_f(t) = |\langle f|T|P^0\rangle|^2$, $\bar{P}_{\bar{f}}(t) = |\langle \bar{f}|T|\bar{P}^0\rangle|^2$. In case of the presented study, two decay probabilities correspond to two CPT-conjugate decays: $\bar{D}^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$, respectively. Decaying D^0 mesons originate from the $D^{*+}(2010) \to D^0\pi^+$ produced directly at the pp collision vertex. The electric charge of the low-momentum pion in the D^{*+} decay indicates the flavour of the decaying D^0 meson, while the final-state flavour is determined by the pion charge from the D^0 decay. When both pions are of the same sign, the decay asymmetry is called right-sign (RS). The weak decays are classified into Cabibbo-favoured (CF), Cabibbo-suppressed (CS), and doubly-Cabibbo-suppressed (DCS) decays, depending on the level of suppression related to the sine of the Cabibbo angle λ that appears in their decay amplitude [15, 16]. The RS asymmetry in Eq. (5) is constructed from decays that receive both large CF (A_{CF}) and small DCS contribution (A_{DCS}), which makes the asymmetry almost purely flavour-specific. The A_{CF} and A_{DCS} represent decay amplitudes at production. Approximation of Eq. (5) to the first order in x, y leads to

$$\begin{aligned} A_{\mathrm{CPT}}(t) &= A_{\mathrm{dir}} + (\mathrm{Re}(z)y - \mathrm{Im}(z)x)\Gamma t \\ &\quad -\frac{\sqrt{R_{\mathrm{DCS}}}}{2}\sqrt{|1-z^2|} \\ &\quad \times \left\{ \sin\phi \left[x\cos(\delta+\kappa) - y\sin(\delta+\kappa)\right]\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right. \\ &\quad \left. -\cos\phi\left[y\cos(\delta+\kappa) + x\sin(\delta+\kappa)\right]\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right\}\Gamma t\,, \end{aligned} \tag{6}$$

where $\kappa \equiv 0.5\arg(1-z^2)$, $R_{\mathrm{DCS}} \equiv |A_{\mathrm{DCS}}/A_{\mathrm{CF}}|^2$, weak phase difference $\phi \equiv \arg(q/p)$, and the strong phase difference $\delta \equiv \arg(A_{\mathrm{CF}}/A_{\mathrm{DCS}})$. The fact that both contributions occur via tree-level diagrams dominated by a single weak phase leads to negligible direct CP symmetry violation[2] A_{dir} [13].

4. Experimental study of CPTV in charm decays

The first experimental search for the CPTV in the $D^0 \to K^-\pi^+$ channel was performed by the FOCUS Collaboration [5]. Due to small statistics of 35 thousand event candidates, the estimated limits for the expression $y\,\mathrm{Re}(z) - x\,\mathrm{Im}(z)$ provided rather loose bounds of the order $\mathcal{O}(1)$, which represented the strongest bounds on CPTV in the charm sector until the calculation in [9] was made. The slope of the linear fit (6) to the time-dependent RS asymmetry can be identified as the $y\,\mathrm{Re}(z) - x\,\mathrm{Im}(z)$ term, provided the SM-compliant CP-related term proportional to $\sqrt{R_{\mathrm{DCS}}}$ is small. This term was marked as blue in the left panel of Fig. 1 representing experimental limits in the $(\mathrm{Re}(z), \mathrm{Im}(z))$ representation. The parameters needed to estimate the effect of CPV are taken from the HFLAV fits [14]. In the estimation of this term, it was assumed that the CPTV is small $|z|^2 \ll 1$.

The high-statistics time-dependent asymmetry in $D^0 \to K^-\pi^+$ decay channel was determined by LHCb [17]. The slope resulting from the linear fit to data was measured to be $s = (-4 \pm 5 \pm 2) \times 10^{-5}$, where the uncertainties correspond to statistical and systematic, respectively [17]. The result is consistent with zero within one statistical standard deviation. The real and imaginary parts of z cannot be disentangled from this fit without further assumptions. However, the constraint on s restricts the possible values of δm and $\delta\Gamma$. As it was shown in [9], $\delta m(\phi) = s\,\Gamma\,\frac{x + y\tan\phi}{y - x\tan\phi}$, $\delta\Gamma = 2\,s\,\Gamma$, where $\phi = \arg(z)$. This leads to the following constraints: $(-4.7 < \delta\Gamma < 2.1) \times 10^{-16}$ GeV at 95% C.L., $(-2.0 < \delta m < 2.0) \times 10^{-15}$ GeV for 95% of

[2] The CP violation can manifest in three ways: directly in decay amplitudes or indirectly in either mixing, or interference between mixing and decays [16].

$\arg(z)$ (we cut out 5% of the $\phi = \arg(z)$ arguments for which $|\delta m(\phi)|$ is the greatest). These constraints are two orders of magnitude stricter compared to their analogues from Ref. [5]. The constraint on $\delta m(\phi)$ is conditional on the value of $\phi = \arg(z)$ (Fig. 1, right). In particular, we observe the asymptotic behaviour in the neighbourhood of $\arg(z) = \mathrm{Arctan}(\frac{y}{x})$.

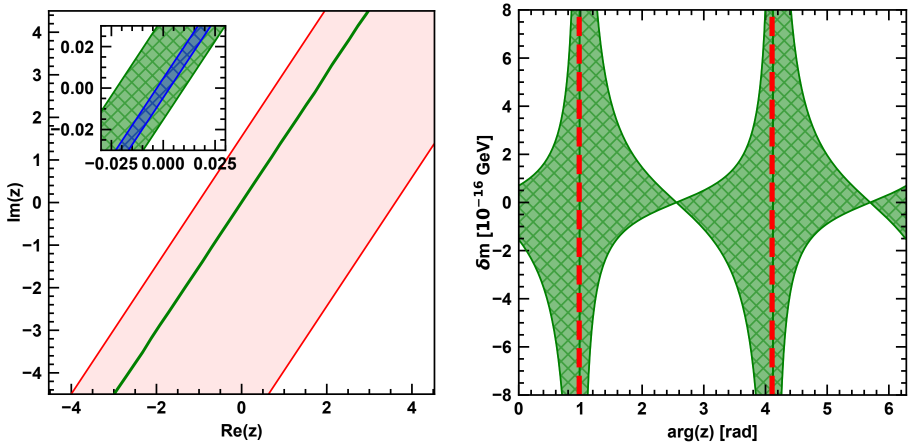

Fig. 1. Left plot: Experimental limits on the CPT-violating z parameter at the 95% confidence level (C.L.) in the $D^0 \to K^-\pi^+$ channel, as reported by the FOCUS Collaboration [5] (red area) and inferred from the LHCb measurement [17] (green area). The uncertainty arising from potential SM-compliant CPV is represented by the blue area. Right plot: Distribution of the mass difference δm as a function of $\phi = \arg(z)$. The green area represents the 95% C.L., while the red dashed lines indicate the values of ϕ for which δm is undefined due to the vanishing of the linear asymmetry term. The figures are adapted from [9].

In order to place any bounds on δm in this neighbourhood, we would need to consider higher-order terms in x, y in Eq. (6) and relax the assumption on the smallness of $|z|$.

5. Prospects in the SME

In the SME framework, the CPTV parameter z is not constant but depends on both the momentum and sidereal time $\hat{t}$, and can be written as [11]

$$z\left(p, \hat{t}\,\right) = \frac{\gamma(p)\left[\Delta a_0 + \beta(p)\Delta a_Z \cos\chi + \beta(p)\sin\chi\left(\Delta a_Y \sin\varOmega\hat{t} + \Delta a_X \cos\varOmega\hat{t}\,\right)\right]}{\varGamma(x - iy)}\,, \quad (7)$$

where γ denotes the Lorentz factor and β is the four-velocity. The Ω is the sidereal frequency. Parameter χ is the factor related to the geographical location of the lab, while the Δa_μ CPTV parameters are expressed in the Sun-centred reference frame of fixed stars. The Z-axis is directed North, following the rotation axis of Earth, the X-axis points away from the Sun at the vernal equinox, and the Y-axis complements the right-handed coordinate system.

In SME, the four Δa_μ coefficients are real numbers, which leads to the vanishing of the linear term $y\,\mathrm{Re}(z) - x\,\mathrm{Im}(z)$. Therefore, the higher-order terms must be taken into account. In this framework, the only assumption on the smallness of z or Δa_μ is related to the fact that Δa_μ is derived in the context of the general renormalizable effective field theory and therefore assumes that the coupling coefficients of each quark to the Lorentz-violating field ($a_\mu^{q_1}$, $a_\mu^{q_2}$) are perturbative. The coefficients are related to the observable through $\Delta a_\mu = a_\mu^{q_1} - a_\mu^{q_2}$. In the D^0 system, the coupling coefficients should be much smaller than the charm mass of the order of 1 GeV, which is well above the energy scale of 10^{-13} GeV corresponding to the current best measurement by FOCUS [5]. However, in some scenarios where the Lorentz- and CPT-violating effects are regarded as originating from a more fundamental theory, the magnitude of these coefficients is expected to be of the order of the Planck scale [18]. Between 2011–2018, the LHCb experiment has collected 10^4 times more events in the $D^0 \to K^-\pi^+$ decay mode compared to the FOCUS experiment. Roughly, this should lead to an improvement of the factor of 100 in terms of the limits on the Δa_μ parameters for this decay channel.

REFERENCES

[1] M.S. Sozzi, «Discrete Symmetries and CP Violation: From Experiment to Theory», *Oxford University Press*, New York 2008.

[2] A. Bevilacqua, J. Kowalski-Glikman, W. Wiślicki, *Phys. Rev. D* **105**, 105004 (2022).

[3] G. Amelino-Camelia, *Int. J. Mod. Phys. D* **11**, 35 (2002).

[4] J. Bernabeu, N.E. Mavromatos, J. Papavassiliou, *Phys. Rev. Lett.* **92**, 131601 (2004).

[5] FOCUS Collaboration (J.M. Link *et al.*), *Phys. Lett. B* **556**, 7 (2003).

[6] KLOE-2 Collaboration, *Phys. Lett. B* **845**, 138164 (2023).

[7] LHCb Collaboration (R. Aaij *et al.*), *Phys. Rev. Lett.* **116**, 241601 (2016).

[8] V.A. Kostelecký, N. Russell, *Rev. Mod. Phys.* **83**, 11 (2011).

[9] W. Krzemień, M. Kmieć, A. Szableski, W. Wiślicki, *Phys. Rev. D* **110**, 055021 (2024).

[10] D. Colladay, V.A. Kostelecký, *Phys. Rev. D* **55**, 6760 (1997).

[11] V.A. Kostelecký, *Phys. Rev. D* **64**, 076001 (2001).

[12] V. Weisskopf, E. Wigner, *Z. Phys.* **63**, 54 (1930).

[13] Particle Data Group (R.L. Workman *et al.*), *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).

[14] Heavy Flavor Averaging Group Collaboration (Y. Amhis *et al.*), *Phys. Rev. D* **107**, 052008 (2023).

[15] LHCb Collaboration (R. Aaij *et al.*), *J. High Energy Phys.* **2019**, 084 (2019).

[16] Y. Grossman, A.L. Kagan, Y. Nir, *Phys. Rev. D* **75**, 036008 (2007).

[17] LHCb Collaboration (R. Aaij *et al.*), *Phys. Rev. D* **104**, 072010 (2021).

[18] V.A. Kostelecký, R. Lehnert, *Phys. Rev. D* **63**, 065008 (2001).