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CP-violation in charm

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I review recent results in theoretical and experimental analyses of CP-violation in charmed transitions, paying particular attention to constraints on parameters of beyond the Standard Model interactions.

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1 Introduction

Charm transitions play an important role in flavor physics. Along with the corresponding searches in strange and beauty-flavored systems, charm provide outstanding opportunities for indirect searches for physics beyond the Standard Model (SM). These searches yield stringent constraints on the models of New Physics (NP) because of the availability of large statistical samples of charm data [1].

One of the most important tools in indirect studies of New Physics is the observation of CP-violation. The Standard Model's picture of CP-violation [2] is related to the phases of the coupling constants of dimension-four operators describing quark Yukawa interactions with Higgs fields ϕ,

$$\mathcal{L}_Y = \xi_{ik}\overline{\psi}_i\psi_k\phi + \text{ h.c.} \tag{1}$$

These complex Yukawa couplings ξ_{ik} lead to a complex-valued Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix providing a natural source of CP-violation for the case of the Standard Model with three (or more) generations. The SM with three generations has a single CP-violating phase, making it a very restrictive system with a possibility to relate observed effects in quark systems with different flavors. This mechanism was experimentally confirmed in the observations of oscillations and decays of beauty and strange mesons.

This is clearly not a unique way of introducing CP-violation in Quantum Field Theory. Another way involves adding operators of dimensions less than four (the "soft" CP-breaking), which is popular in supersymmetric models. Yet another way is to break CP-invariance spontaneously. This method, which is somewhat aesthetically appealing, introduces a CP-violating ground state with a CP-conserved Lagrangian. It is realized in a class of left-right-symmetric models or multi-Higgs models. All these mechanisms can be probed in charm transitions.

It can be argued that the observation of CP-violation in the current round of charm experiments constitutes one of the signals of physics beyond the Standard Model (BSM). This argument stems from the fact that all quarks that build up initial and final hadronic states in weak decays of charm mesons or baryons belong to the first two generations. This implies that those transitions are governed by a 2×2 Cabibbo quark mixing matrix. This matrix is real, so no CP-violation is possible in the dominant tree-level diagrams which describe the decay amplitudes. In the Standard Model, CP-violating amplitudes in charm transitions can be introduced by including penguin or box operators induced by virtual b-quarks. However, their contributions are strongly suppressed by the small combination of CKM matrix elements $V_{cb}V_{ub}^*$. Explicit evaluations of b-quark contributions to mixing asymmetries yield results of the order of $0.1 - 1\%$ [3] with similar predictions for decay amplitudes [4]. Thus, observation of larger CP violation in charm decays or mixing would be an unambiguous sign for new physics.

As with other flavor physics, CP-violating contributions in charm can be generally classified by three different categories:

(I) CP violation in the $D^0 - \overline{D^0}$ mixing matrix (or "indirect" CP-violation). Introduction of $\Delta C = 2$ transitions, either via SM or NP one-loop or tree-level NP amplitudes leads to non-diagonal entries in the $D^0 - \overline{D}^0$ mass matrix,

$$\left[M - i\frac{\Gamma}{2}\right]_{ij} = \begin{pmatrix} A & p^2 \\ q^2 & A \end{pmatrix} \tag{2}$$

This type of CP violation is manifest when $R_m^2 = |p/q|^2 = (2M_{12} - i\Gamma_{12})/(2M_{12}^* - i\Gamma_{12}^*) \neq 1$.

(II) CP violation in the $\Delta C = 1$ decay amplitudes (or "direct" CP-violation). This type of CP violation occurs when the absolute value of the decay amplitude for D to decay to a final state f (A_f) is different from the one of the corresponding CP-conjugated amplitude ("direct CP-violation"). This can happen if the decay amplitude can be broken into at least two parts associated with different weak and strong phases,

$$A_f = |A_1|\, e^{i\delta_1} e^{i\phi_1} + |A_2|\, e^{i\delta_2} e^{i\phi_2}, \tag{3}$$

where ϕ_i represent weak phases ($\phi_i \to -\phi_i$ under CP-transormation), and δ_i represents strong phases ($\delta_i \to \delta_i$ under CP-transformation). This ensures that the CP-conjugated amplitude, $\overline{A}_{\overline{f}}$ would differ from A_f.

(III) CP violation in the interference of decays with and without mixing. This type of CP violation is possible for a subset of final states to which both D^0 and $\overline{D^0}$ can decay.

For a given final state f, CP violating contributions can be summarized in the parameter

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = R_m e^{i(\phi+\delta)} \left|\frac{\overline{A}_f}{A_f}\right|, \tag{4}$$

where A_f and $\overline{A}_f$ are the amplitudes for $D^0 \to f$ and $\overline{D^0} \to f$ transitions respectively and δ is the CP-conserving strong phase difference between A_f and $\overline{A}_f$. In Eq. (4) ϕ represents the convention-independent CP-violating phase difference between the ratio of decay amplitudes and the mixing matrix.

2 Indirect CP-violation

The non-diagonal entries in the mixing matrix of Eq. (2) lead to mass eigenstates of neutral D-mesons that are different from the weak eigenstates. They, however, are related by a linear transformation,

$$|D_{\frac{1}{2}}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \tag{5}$$

where the complex parameters p and q are obtained from diagonalizing the $D^0 - \overline{D}^0$ mass matrix of Eq. (2). Note that if CP-violation is neglected, $p = q = 1/\sqrt{2}$. The mass and width splittings between mass eigenstates are

$$x_D = \frac{m_1 - m_2}{\Gamma_D}, \qquad y_D = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}, \tag{6}$$

where $\Gamma_{\rm D}$ is the average width of the two neutral D meson mass eigenstates. Because of the absence of superheavy down-type quarks destroying Glashow-Iliopoulos-Maiani (GIM) cancellation, it is expected that x_D and y_D should be rather small in the Standard Model. The quantities which are actually measured in experimental determinations of the mass and width differences, are $y_{\rm D}^{\rm (CP)}$ (measured in time-dependent $D \to KK, \pi\pi$ analyses), $x'_{\rm D}$, and $y'_{\rm D}$ (measured, e.g., in $D \to K\pi$ or similar transitions), are defined as

$$\begin{aligned} y_{\rm D}^{\rm (CP)} &= y_{\rm D} \cos\phi - x_{\rm D} \sin\phi \left(\frac{A_m}{2} - A_{prod} \right) \quad , \\ x'_D &= x_D \cos\delta_{K\pi} + y_D \sin\delta_{K\pi} \quad , \\ y'_D &= y_{\rm D} \cos\delta_{K\pi} - x_{\rm D} \sin\delta_{K\pi} \quad , \end{aligned} \tag{7}$$

where $A_{prod} = \left(N_{D^0} - N_{\overline{D}^0} \right) / \left(N_{D^0} + N_{\overline{D}^0} \right)$ is the so-called production asymmetry of D^0 and $\overline{D}^0$ (giving the relative weight of D^0 and $\overline{D}^0$ in the sample) and $\delta_{K\pi}$ is the strong phase difference between the Cabibbo favored and double Cabibbo suppressed amplitudes [5], which can be measured in $D \to K\pi$ transitions. A CP-violating phase ϕ is defined in Eq. (4). A fit to the current database of experimental analyses by the Heavy Flavor Averaging Group (HFAG) gives [6, 7]

$$\begin{aligned} &x_{\rm D} = 0.0100^{+0.0024}_{-0.0026} \ , \qquad &y_{\rm D} = 0.0076^{+0.0017}_{-0.0018} \ , \\ &1 - |q/p| = 0.06 \pm 0.14, \quad &\phi = -0.05 \pm 0.09. \end{aligned} \tag{8}$$

At this stage it is important to note that the size of the signal allows to conclude that the former "smoking gun" signal for New Physics in $D^0 - \overline{D}^0$ mixing, $x \gg y$ no longer applies. Now, even though theoretical calculations of x_D and y_D are quite uncertain, the values $x_D \sim y_D \sim 1\%$ are natural in the Standard Model [8]. Also, as was argued earlier, CP-violation asymmetries in charm mixing are quite small. The question that arises now is how to use the data provided by Eq. (8) to probe physics beyond the SM.

This question can be answered using an effective field theory approach. Heavy BSM degrees of freedom cannot be directly produced in charm meson decays, but can nevertheless affect the effective $|\Delta C| = 2$ Hamiltonian by changing Wilson coefficients and/or introducing new operator structures*. By integrating out those new degrees of freedom associated with new interactions at a high scale M, we are left with an effective hamiltonian written in the form of a series of operators of increasing dimension. It turns out that a model-independent study of NP $|\Delta C| = 2$ contributions is possible, as any NP model will only modify Wilson coefficients of those operators [10, 11],

$$\mathcal{H}_{NP}^{|\Delta C|=2} = \frac{1}{M^2}\left[\sum_{i=1}^{8} \mathrm{C}_i(\mu)\ Q_i\right], \tag{9}$$

where C_i are dimensionless Wilson coefficients, and the Q_i are the effective operators:

$$\begin{array}{ll} Q_1 = (\overline{u}_L^\alpha \gamma_\mu c_L^\alpha)\ (\overline{u}_L^\beta \gamma^\mu c_L^\beta)\ , & Q_5 = (\overline{u}_R^\alpha c_L^\beta)\ (\overline{u}_L^\beta c_R^\alpha)\ , \\ Q_2 = (\overline{u}_R^\alpha c_L^\alpha)\ (\overline{u}_R^\beta c_L^\beta)\ , & Q_6 = (\overline{u}_R^\alpha \gamma_\mu c_R^\alpha)\ (\overline{u}_R^\beta \gamma^\mu c_R^\beta)\ , \\ Q_3 = (\overline{u}_R^\alpha c_L^\beta)\ (\overline{u}_R^\beta c_L^\alpha)\ , & Q_7 = (\overline{u}_L^\alpha c_R^\alpha)\ (\overline{u}_L^\beta c_R^\beta)\ , \\ Q_4 = (\overline{u}_R^\alpha c_L^\alpha)\ (\overline{u}_L^\beta c_R^\beta)\ , & Q_8 = (\overline{u}_L^\alpha c_R^\beta)\ (\overline{u}_L^\beta c_R^\alpha)\ \ , \end{array} \tag{10}$$

here α and β are color indices. In total, there are eight possible operator structures that exhaust the list of possible independent contributions to $|\Delta C| = 2$ transitions†. Taking operator mixing into account, a set of constraints on the Wilson coefficients of Eq. (9) can be placed,

$$\begin{array}{ll} |C_1| \leq 5.7 \times 10^{-7} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, & \\ |C_2| \leq 1.6 \times 10^{-7} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, & |C_4| \leq 5.6 \times 10^{-8} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, \\ & |C_5| \leq 1.6 \times 10^{-7} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2. \\ |C_3| \leq 5.8 \times 10^{-7} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, & \end{array} \tag{11}$$

The constraints on $C_6 - C_8$ are identical to those on $C_1 - C_3$ [10]. Note that Eq. (11) implies that New Physics particles, for some unknown reason, have highly suppressed couplings to charmed quarks. Alternatively, the tight constraints of Eq. (11) probes NP at very high scales: $M \geq (4-10) \times 10^3$ TeV for tree-level NP-mediated charm mixing and $M \geq (1-3) \times 10^2$ TeV for loop-dominated mixing via New Physics particles.

No CP-violation has been observed in charm transitions yet. However, available experimental constraints of Eq. (8) can provide some tests of CP-violating NP models. For example, a set of constraints on the imaginary parts of Wilson coefficients of

*NP can also affect $|\Delta C| = 1$ transitions and thus contribute to y_D. For more details, see [9].

†Note that earlier Ref. [11] used a slightly different set of operators than [10], which can be related to each other by a linear transformation.

Eq. (9) can be placed,

$$\begin{aligned}
&\mathrm{Im}\,[C_1] \le 1.1 \times 10^{-7} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, \qquad && \mathrm{Im}\,[C_4] \le 1.1 \times 10^{-8} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, \\
&\mathrm{Im}\,[C_2] \le 2.9 \times 10^{-8} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, && \mathrm{Im}\,[C_5] \le 3.0 \times 10^{-8} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2. \\
&\mathrm{Im}\,[C_3] \le 1.1 \times 10^{-7} \left[\frac{M}{1\ \mathrm{TeV}}\right]^2, &&
\end{aligned} \tag{12}$$

Just like the constraints of Eq. (11), they give a sense of how NP particles couple to the Standard Model.

Other tests can also be performed. For instance, neglecting direct CP-violation in the decay amplitudes, one can write a "theory-independent" relation among $D^0 - \overline{D}^0$ mixing amplitudes [12, 13],

$$\frac{x}{y} = \frac{1 - |q/p|}{\tan\phi} \tag{13}$$

Current experimental results $x/y \approx 0.8 \pm 0.3$ imply that amount of CP-violation in the $D^0 - \overline{D}^0$ mixing matrix is comparable to CP-violation in the interference of decays and mixing amplitudes.

3 Direct CP-violation

In principle, $D^0 - \overline{D}^0$ mixing is not required for the observation of CP-violation. While CPT-symmetry requires the total widths of D and $\overline{D}$ to be the same, the partial decay widths $\Gamma(D \to f)$ and $\Gamma(\overline{D} \to \overline{f})$ could be different in the presence of CP-violation, which would be signaled by a non-zero value of the asymmetry

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}. \tag{14}$$

One can also introduce a related asymmetry $a_{\overline{f}}$ by substituting $f \to \overline{f}$ in Eq. (14). For charged D-decays the only contribution to the asymmetry of Eq. (14) comes from the multi-component structure of the $\Delta C = 1$ decay amplitude of Eq. (3). In this case,

$$a_f \;=\; \frac{2Im\,(A_1 A_2^*) \sin\delta}{|A_1|^2 + |A_2|^2 + 2Re A_1 A_2^* \cos\delta} = 2 r_f \sin\phi \sin\delta, \tag{15}$$

where $\delta = \delta_1 - \delta_2$ is the CP-conserving phase difference and ϕ is the CP-violating one. $r_f = |A_2/A_1|$ is the ratio of amplitudes. Both r_f and δ are extremely difficult to compute reliably in D-decays. However, the task can be significantly simplified if one only concentrates on detection of New Physics in CP-violating asymmetries in the current round of experiments [14], i.e. at the $\mathcal{O}(1\%)$ level. This is the level at which a_f is currently probed experimentally, see, e.g. [15]. As follows from Eq. (15), in this case one should expect $r_f \sim 0.01$.

It is easy to see that the Standard Model asymmetries are safely below this estimate. First, Cabibbo-favored ($A_f \sim \lambda^0$) and doubly Cabibbo-suppressed ($A_f \sim \lambda^2$) decay modes proceed via amplitudes that share the same weak phase, so no CP-asymmetry is generated‡. On the other hand, singly-Cabibbo-suppressed decays ($A_f \sim \lambda^1$) readily have a two-component structure, receiving contributions from both tree and penguin amplitudes. In this case the same conclusion follows from the consideration of the charm CKM unitarity, $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$.

In the Wolfenstein parameterization of CKM, the first two terms in this equation are of the order $\mathcal{O}(\lambda)$ (where $\lambda \simeq 0.22$), while the last one is $\mathcal{O}(\lambda^5)$. Thus, the CP-violating asymmetry is expected to be at most $a_f \sim 10^{-3}$ in the SM. Model-dependent estimates of this asymmetry exist and are consitent with this estimate [4].

Asymmetries of Eq. (14) can also be introduced for the neutral D-mesons. In this case a much richer structure becomes available due to interplay of CP-violating contributions to decay and mixing amplitudes [5, 14],

$$
\begin{aligned}
a_f &= a_f^d + a_f^m + a_f^i, \\
a_f^d &= 2r_f \sin\phi \sin\delta, \\
a_f^m &= -R_f \frac{y'}{2}\left(R_m - R_m^{-1}\right)\cos\phi, \\
a_f^i &= R_f \frac{x'}{2}\left(R_m + R_m^{-1}\right)\sin\phi,
\end{aligned} \tag{16}
$$

where a_f^d, a_f^m, and a_f^i represent CP-violating contributions from decay, mixing and interference between decay and mixing amplitudes respectively. For the final states that are also CP-eigenstates, $f = \overline{f}$ and $y' = y$. All those asymmetries can be studied experimentally.

4 Conclusions and outlook

Studies of CP-violation will help to distinguish among the models of New Physics describing new particles possibly observed at the Large Hadron Collider (LHC) in the upcoming years. Recent studies of charm quark observables already revealed puzzling non-universality of possible NP contributions to low energy flavor-changing transitions. In particular, no new signals of CP-violation have been observed.

An extensive experimental study of exclusive decays should be performed [14], shedding new light on how large CP-violation in charm transition amplitudes could

‡Technically, there is a small, $\mathcal{O}(\lambda^4)$ phase difference between the dominant tree T amplitude and exchange E amplitudes.

be. Finally, new observables, such as CP-violating "untagged" decay asymmetries [16] should be studied in hadronic decays of charmed mesons. These analyses will be be indispensable for physics of the LHC era.

References

[1] For recent reviews see M. Artuso, B. Meadows and A. A. Petrov, Ann. Rev. Nucl. Part. Sci. **58**, 249 (2008). A. A. Petrov, PoS **BEAUTY2009**, 024 (2009) [arXiv:1003.0906 [hep-ph]]; S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7**, 1 (2003); G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431 (2003); X. Q. Li, X. Liu and Z. T. Wei, Front. Phys. China **4**, 49 (2009).

[2] I. I. Bigi and A. I. Sanda, *CP violation* (Cambridge University Press, 2000).

[3] M. Bobrowski, A. Lenz, J. Riedl and J. Rohrwild, JHEP **1003**, 009 (2010); I. I. Y. Bigi and A. I. Sanda, arXiv:hep-ph/9909479.

[4] F. Buccella, M. Lusignoli, G. Mangano, G. Miele, A. Pugliese and P. Santorelli, Phys. Lett. B **302**, 319 (1993).

[5] S. Bergmann, *et. al*, Phys. Lett. B **486**, 418 (2000); A. F. Falk, Y. Nir and A. A. Petrov, JHEP **9912**, 019 (1999).

[6] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007); M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007); K. Abe *et al.* [BELLE Collaboration], Phys. Rev. Lett. **99**, 131803 (2007).

[7] Heavy Flavor Averaging Group (HFAG), http://www.slac.stanford.edu/xorg/hfag/charm/

[8] A. F. Falk, Y. Grossman, Z. Ligeti and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002); A. F. Falk, *et. al*, Phys. Rev. D **69**, 114021 (2004); J. Donoghue, E. Golowich, B. Holstein and J. Trampetic, Phys. Rev. D33, 179 (1986); L. Wolfenstein, Phys. Lett. B164, 170 (1985); P. Colangelo, G. Nardulli and N. Paver, Phys. Lett. B242, 71 (1990); T.A. Kaeding, Phys. Lett. B357, 151 (1995); for other approaches, see H. Georgi, Phys. Lett. B297, 353 (1992); T. Ohl, G. Ricciardi and E. Simmons, Nucl. Phys. B403, 605 (1993); I. Bigi and N. Uraltsev, Nucl. Phys. B **592**, 92 (2001).

[9] E. Golowich, S. Pakvasa and A. A. Petrov, Phys. Rev. Lett. **98**, 181801 (2007).

[10] O. Gedalia, Y. Grossman, Y. Nir and G. Perez, Phys. Rev. D **80**, 055024 (2009).

[11] E. Golowich,et. al, Phys. Rev. D **76**, 095009 (2007).

[12] Y. Grossman, Y. Nir and G. Perez, Phys. Rev. Lett. **103**, 071602 (2009).

[13] A. L. Kagan and M. D. Sokoloff, Phys. Rev. D **80**, 076008 (2009).

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

[15] CDF Collaboration, CDF note 10296.

[16] A. A. Petrov, Phys. Rev. D **69**, 111901 (2004).