

Implications of CP-violation in charmed hadrons

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Abstract. I discuss theoretical implications of recent experimental progress in understanding CP-violation in charmed mesons. I discuss recent standard model predictions and attempts to constrain beyond the standard model scenarios using observations of charm hadron transitions.

1. Introduction

CP-violation has never been observed in the up-quark sector. This is in stark contrast to the bottom-type quarks, where CP-violating effects have been seen in both s and b -quark transitions. While current experimental constraints do not support a possibility of large new physics (NP) enhancement of the expected signals in the up-quark sector, a modest NP contribution is still possible. It is therefore important to constrain the size of possible NP interactions, or, at least determine the size of the standard model (SM) signal.

Among the studies of flavor physics in the up quark sector, charm transitions play an outmost important role. Charm quark is the only up-type quark that can undergo flavor oscillations, which makes it the only currently viable probe of $\Delta Q = 2$ interactions there. Besides that, the availability of large statistical samples of charm data makes charm system one of the most convenient places to put constraints on NP interactions [1]. Depending on the source of CP-violating interactions, it is often convenient to classify the CP-violating contributions in charm according to the number of units of charm quantum number the corresponding operators change. In other words,

- (I) **CP-violation in $\Delta C = 2$ transitions.** Both SM and NP can generate local operators at the charm quark mass scale that change charm quantum number by two units. Yet, NP CP-violating interactions can have a different origin from the SM ones, where they came from the same Yukawa couplings – or complex-valued matrix elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [2] – and contribute to both $\Delta C = 2$ and $\Delta C = 1$ effective operators. Phenomenologically, one can distinguish CP violation that originates in the $D^0\bar{D}^0$ mixing matrix (aka “indirect” CP-violation) from other sources of CP-violation. The non-diagonal entries in the $D^0 - \bar{D}^0$ mass matrix,

$$\left[M - i\frac{\Gamma}{2} \right]_{ij} = \begin{pmatrix} A & p^2 \\ q^2 & A \end{pmatrix} \quad (1)$$

can lead to manifest effects of CP-violation when $R_m^2 = |p/q|^2 = (2M_{12} - i\Gamma_{12})/(2M_{12}^* - i\Gamma_{12}^*) \neq 1$. Also, CP violation in the interference of decays with and without mixing can be

detected. This type of CP violation is possible for a subset of final states to which both D^0 and \bar{D}^0 can decay.

- (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 final state in the decay can be reached via at least two different “pathways” whose amplitudes are associated with different weak and strong phases,

$$A_f = |A_1| e^{i\delta_1} e^{i\phi_1} + |A_2| e^{i\delta_2} e^{i\phi_2}, \quad (2)$$

where ϕ_i represent weak phases (odd under CP), and δ_i represents strong phases (even under CP). This ensures that the CP-conjugated amplitude, $\bar{A}_{\bar{f}}$ is different from A_f .

Contrary to the case of bottom quarks, standard model interactions do not produce a large CP-violating signal in charmed system. 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, at tree level, 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 can be introduced by including penguin or box operators induced by virtual b -quarks, which gives a needed access to the third generation of 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]. How would those effects manifest themselves in experimental observables?

While CPT-symmetry requires the total widths of D and \bar{D} to be the same, the partial decay widths $\Gamma(D \rightarrow f)$ and $\Gamma(\bar{D} \rightarrow \bar{f})$ could be different in the presence of CP-violation, which would be signaled by a non-zero value of the asymmetry

$$a_f = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}, \quad (3)$$

which, depending on the final and initial state, can be generated by both $\Delta C = 1$ and $\Delta C = 2$ interactions.

Asymmetries of Eq. (3) can be introduced for both charged and neutral D -mesons. In the latter case a much richer structure becomes available due to interplay of CP-violating contributions to decay and mixing amplitudes [5, 6], which can play the role of a “second pathway,”

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

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 (we shall introduce a_f^d momentarily). Note that for the final states that are also CP-eigenstates $f = \bar{f}$ and $y' = y$.

Early experimental hints at larger, about a few percent, values of the combined asymmetry,

$$\Delta A_{CP} = a_{KK} - a_{\pi\pi}, \quad (4)$$

led to active theoretical reevaluations of the size of the SM contribution to this asymmetry, as observation of larger CP violation in charm decays or mixing was assumed to be an unambiguous sign for new physics. We shall discuss those models in Section 3.

Finally, it is convenient to define, for a given final state f , a measure that parameterizes CP violating contributions,

$$\lambda_f = \frac{q \bar{A}_f}{p A_f} = R_m e^{i(\phi+\delta)} \left| \frac{\bar{A}_f}{A_f} \right|, \quad (5)$$

where A_f and \bar{A}_f are the amplitudes for $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow f$ transitions respectively and δ is the CP-conserving strong phase difference between A_f and \bar{A}_f . In Eq. (5) ϕ represents the convention-independent CP-violating phase difference between the ratio of decay amplitudes and the mixing matrix.

2. CP-violation in $\Delta C = 2$ transitions.

The non-diagonal entries in the mixing matrix of Eq. (1) lead to mass eigenstates of neutral D -mesons that are different from the weak eigenstates. They, however, are related by a linear transformation,

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle, \quad (6)$$

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

$$x_D = \frac{m_1 - m_2}{\Gamma_D}, \quad y_D = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}, \quad (7)$$

where Γ_D is the average width of the two neutral D meson mass eigenstates. The mixing parameters above can be related to real and imaginary parts of the correlation function,

$$\begin{aligned} x_D &= \frac{1}{2m_D\Gamma_D} \text{Re} \left[\langle \bar{D}^0 | H^{\Delta C=2} | D^0 \rangle + \langle \bar{D}^0 | i \int d^4x \text{T} \left[H^{\Delta C=1}(x) H^{\Delta C=1}(0) \right] | D^0 \rangle \right], \\ y_D &= \frac{1}{2m_D\Gamma_D} \text{Im} \left[\langle \bar{D}^0 | i \int d^4x \text{T} \left[H^{\Delta C=1}(x) H^{\Delta C=1}(0) \right] | D^0 \rangle \right], \end{aligned} \quad (8)$$

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. Moreover, since the integral in Eq. (8) is not necessarily dominated by short distances, the expectation is that the theoretical calculation of x_D and y_D is rather uncertain. A fit to the current database of experimental analyses by the Heavy Flavor Averaging Group (HFAG) gives, allowing for CP-violation [7, 8]

$$\begin{aligned} x_D &= 0.41_{-0.15}^{+0.14}\%, \quad y_D = 0.63_{-0.08}^{+0.07}\% , \\ |q/p| &= 0.93_{-0.08}^{+0.09}, \quad \phi = -8.7_{-9.1}^{+8.7} \text{ degrees.} \end{aligned} \quad (9)$$

CP-violation induced by $\Delta C = 2$ operators can be best studied in the “super weak” limit¹, that is, neglecting direct CP-violation in the decay amplitudes.

It is easy to see that in this limit the number of “experimental” parameters (x_D , y_D , $|q/p|$, and ϕ of Eq. (9)), exceeds the number of “theoretical” parameters ($|M_{12}|$, $|\Gamma_{12}|$, and

¹ We borrow this terminology from kaon physics, where this phrase was coined by L. Wolfenstein to understand origins of CP-violation in that system.

$\phi_{12} = \arg(M_{12}/\Gamma_{12})$, so one can write a "theory-independent" constraint relation among $D^0\bar{D}^0$ mixing amplitudes [9, 10],

$$\frac{x_D}{y_D} = \frac{1 - |q/p|}{\tan \phi}. \quad (10)$$

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

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 [11], which is approximately what observed experimentally. Also, as was argued earlier, CP-violation asymmetries in charm mixing are quite small. Can we still use charm data to constrain beyond the SM (BSM) scenarios?

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 structures². 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 [13, 14],

$$\mathcal{H}_{NP}^{|\Delta C|=2} = \frac{1}{M^2} \left[\sum_{i=1}^8 C_i(\mu) Q_i \right], \quad (11)$$

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

$$\begin{aligned} Q_1 &= (\bar{u}_L^\alpha \gamma_\mu c_L^\alpha) (\bar{u}_L^\beta \gamma^\mu c_L^\beta), & Q_5 &= (\bar{u}_R^\alpha c_L^\beta) (\bar{u}_L^\beta c_R^\alpha), \\ Q_2 &= (\bar{u}_R^\alpha c_L^\alpha) (\bar{u}_R^\beta c_L^\beta), & Q_6 &= (\bar{u}_R^\alpha \gamma_\mu c_R^\alpha) (\bar{u}_R^\beta \gamma^\mu c_R^\beta), \\ Q_3 &= (\bar{u}_R^\alpha c_L^\beta) (\bar{u}_R^\beta c_L^\alpha), & Q_7 &= (\bar{u}_L^\alpha c_R^\alpha) (\bar{u}_L^\beta c_R^\beta), \\ Q_4 &= (\bar{u}_R^\alpha c_L^\alpha) (\bar{u}_L^\beta c_R^\beta), & Q_8 &= (\bar{u}_L^\alpha c_R^\beta) (\bar{u}_L^\beta c_R^\alpha), \end{aligned} \quad (12)$$

where 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.

No CP-violation has been observed in charm transitions yet. However, available experimental constraints of Eq. (9) can provide some tests of CP-violating NP models. For example, a set of constraints on the imaginary parts of Wilson coefficients of Eq. (11) can be placed,

$$\begin{aligned} \text{Im}[C_1] &\leq 1.1 \times 10^{-7} \left[\frac{M}{1 \text{ TeV}} \right]^2, & \text{Im}[C_4] &\leq 1.1 \times 10^{-8} \left[\frac{M}{1 \text{ TeV}} \right]^2, \\ \text{Im}[C_2] &\leq 2.9 \times 10^{-8} \left[\frac{M}{1 \text{ TeV}} \right]^2, & \text{Im}[C_5] &\leq 3.0 \times 10^{-8} \left[\frac{M}{1 \text{ TeV}} \right]^2. \end{aligned} \quad (13)$$

The constraints on $C_6 - C_8$ are identical to those on $C_1 - C_3$ [13]. Note that Eq. (13) implies that new physics particles, for some unknown reason, have highly suppressed couplings to charmed quarks. Alternatively, the tight constraints of Eq. (13) probe 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.

Other observables could also be interesting in the "superweak" limit. For example, an "untagged" CP-violating asymmetry where one compares decays of a D to a state f to which

² NP can also affect $|\Delta C| = 1$ transitions and thus contribute to y_D . For more details, see [12].

both D^0 and \bar{D}^0 states can decay (but not a CP-eigenstate) without identifying flavor of the initial meson [15, 16] can be considered,

$$A_{CP}^U(f) = \frac{\Sigma_f - \Sigma_{\bar{f}}}{\Sigma_f + \Sigma_{\bar{f}}}, \quad \text{where } \Sigma_f = \Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f), \quad (14)$$

Examples of those states are $f = \pi\rho, KK^*, K^+\pi^-,$ etc.

3. CP-violation in $\Delta C = 1$ transitions.

In principle, $D^0\bar{D}^0$ mixing is not required for the observation of CP-violation³. For charged D -decays the only contribution to the asymmetry of Eq. (3) comes from the multi-component structure of the $\Delta C = 1$ decay amplitude of Eq. (2). In this case,

$$a_f = \frac{2\text{Im}(A_1A_2^*)\sin\delta}{|A_1|^2 + |A_2|^2 + 2\text{Re}A_1A_2^*\cos\delta} = 2r_f\sin\phi\sin\delta, \quad (15)$$

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 [6], i.e. at the $\mathcal{O}(1\%)$ level. This is the level at which a_f is currently probed experimentally, see, e.g. [18]. As follows from Eq. (15), in this case one should expect $r_f \sim 0.01$.

Naively, 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 generated⁴. 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 naively expected to be at most $a_f \sim 10^{-3}$ in the SM. This naive estimate was called in question when a somewhat large value of A_{CP} of Eq. (4) was reported [19] to be

$$\Delta A_{CP} = (-0.678 \pm 0.147)\%. \quad (16)$$

Naively writing decay amplitudes as

$$\begin{aligned} A_{KK} &= \frac{G_F}{\sqrt{2}}\lambda \left[(T + E + P_{sd}) + \lambda^4 e^{-i\gamma} P_{bd} \right], \\ A_{\pi\pi} &= \frac{G_F}{\sqrt{2}}\lambda \left[-(T + E) + P_{sd} + \lambda^4 e^{-i\gamma} P_{bd} \right], \end{aligned} \quad (17)$$

where $T, E, P_{q_1q_2}$ represent tree, exchange, and penguin amplitudes with q_1q_2 intermediate quarks respectively, we can see that in the flavor $SU(3)_F$ limit $\Delta A_{CP} \approx 2a_{KK}$, i.e. somewhat above the naive prediction for the direct CP-violating asymmetry in the standard model.

Re-evaluations of the SM contributions proposed enhancement of penguin amplitudes via various mechanisms, such as variants of $\Delta I = 1/2$ rule for D-decays, large $1/m_c$ corrections,

³ But it is quite important to produce equal amounts of decaying particles and antiparticles, which is a consideration at LHC [17]

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

new fits of flavor-flow diagrams, etc. [20]. Alternatively, a number of new physics scenarios were proposed [21] to explain the result of Eq. (16), as well as means to test them in other charm transitions [22] (see also [23]). The discussions of ΔA_{CP} somewhat muted when LHCb released new analysis of the same quantity, now reporting [8]

$$\Delta A_{CP} = (-0.329 \pm 0.121)\%. \quad (18)$$

While the central value and statistical significance of of this results are much smaller, the question of how to reliably compute ΔA_{CP} is by no means settled [24], so the discussion must continue.

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