

CP violation in charm

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CP-violating asymmetries in charm provide a unique probe of physics beyond the Standard Model. I review several topics relevant to searches for CP-violation in charmed meson and baryon transitions.

1. Introduction

Charm transitions play a unique dual role in the modern investigations of flavor physics. They provide valuable supporting measurements for studies of CP-violation in B -decays, such as formfactors and decay constants, as well as outstanding opportunities for indirect searches for physics beyond the Standard Model (SM). It must be noted that in many dynamical models of new physics the effects of new particles observed in s , c , and b transitions are correlated. Therefore, such combined studies could yield the most stringent constraints on parameters of those models. For example, loop-dominated processes such as $D^0 - \bar{D}^0$ mixing or flavor-changing neutral current (FCNC) decays are influenced by the dynamical effects of *down-type particles*, whereas up-type particles are responsible for FCNC in the beauty and strange systems. Finally, from the practical point of view, charm physics experiments provide outstanding opportunities for studies of New Physics because of the availability of large statistical samples of data.

CP-violation can be introduced in Quantum Field Theory in a variety of ways [1]. One way, CP-violation can be introduced explicitly through dimension-4 operators (the so-called “hard” CP-breaking). This is how CP-invariance is broken in the Standard Model via quark Yukawa interactions,

$$\mathcal{L}_Y = \xi_{ik} \bar{\psi}_i \psi_k \phi + \text{h.c.} \quad (1)$$

The complex Yukawa couplings ξ_{ik} lead to complex-valued Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix providing the natural source of CP-violation for the case of the Standard Model with three (or more) generations. Another way could be via 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 CP-violating ground state with 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. In fact, observation of CP-violation in the current round of charm experiments is arguably one of the cleanest signals of physics beyond the Standard Model (BSM).

It can be easily seen why manifestation of new physics interactions in the charm system is associated with the observation of (large) CP-violation. This is due to the fact that all quarks that build up the hadronic states in weak decays of charm mesons belong to the first two generations. Since 2×2 Cabibbo quark mixing matrix is real, no CP-violation is possible in the dominant tree-level diagrams which describe the decay amplitudes. CP-violating amplitudes can be introduced in the Standard Model 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 $V_{cb}V_{ub}^*$. It is thus widely believed that the observation of (large) CP violation in charm decays or mixing would be an unambiguous sign for new physics. This fact makes charm decays a valuable tool in searching for new physics, since the statistics available in charm physics experiment is usually quite large.

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

- (I) CP violation in the $\Delta C = 1$ decay amplitudes. 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 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,

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

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

- (II) CP violation in $D^0 - \bar{D}^0$ mixing matrix. 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 $D^0 - \bar{D}^0$ mass matrix,

$$\left[M - i \frac{\Gamma}{2} \right]_{ij} = \begin{pmatrix} A & p^2 \\ q^2 & A \end{pmatrix} \quad (3)$$

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

- (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

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

where A_f and \overline{A}_f are the amplitudes for $D^0 \rightarrow f$ and $\overline{D}^0 \rightarrow f$ transitions respectively and δ is the strong phase difference between A_f and \overline{A}_f . Here ϕ represents the convention-independent weak phase difference between the ratio of decay amplitudes and the mixing matrix.

The non-diagonal entries in the mixing matrix of Eq. (3) lead to mass eigenstates of neutral D -mesons that are different from the weak eigenstates,

$$|D_{\pm}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \quad (5)$$

where the complex parameters p and q are obtained from diagonalizing the $D^0 - \overline{D}^0$ mass matrix with $|p|^2 + |q|^2 = 1$. If CP-violation in mixing is neglected, p becomes equal to q , so $|D_{1,2}\rangle$ become CP eigenstates, $CP|D_{\pm}\rangle = \pm|D_{\pm}\rangle$,

$$|D_{\pm}\rangle = \frac{1}{\sqrt{2}} \left[|D^0\rangle \pm |\overline{D}^0\rangle \right] \quad (6)$$

The mass and width splittings between these eigenstates are given by

$$x \equiv \frac{m_2 - m_1}{\Gamma}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}. \quad (7)$$

It is known experimentally that $D^0 - \overline{D}^0$ mixing proceeds extremely slowly, which in the Standard Model is usually attributed to the absence of superheavy quarks destroying GIM cancellations [2, 3, 4]. As we shall see later, this fact additionally complicates searches for CP-violation in charmed mesons.

2. CP-violation in mesons

CP violation can be searched for by a variety of methods. In general, one can separate two ways. One way employs “static” observables, such as electric dipole moment of a baryon. Another way, more applicable to charm physics, employs “dynamical” observables, i.e. decay probabilities and asymmetries. Here we shall concentrate on this methods of searching for CP-violation.

a. CP-violation in transitions, forbidden by CP-invariance. This method is based on the idea that if both initial and final states are prepared as CP-eigenstates, the transition from the initial to final state would be forbidden if their CP-eigenvalues do not match. If CP is broken then transition probability would be proportional to CP-breaking parameter.

While neither of D -mesons constitute a CP-eigenstates, a linear combination of neutral D -mesons of Eq. (6) is. Thus such measurements can be performed at threshold charm factories, such as CLEO-c or BES-III, using quantum coherence of the initial state.

An example of this type of signal is a decay ($D^0\overline{D}^0$) $\rightarrow f_1 f_2$ at $\psi(3770)$ with f_1 and f_2 being the different final CP-eigenstates of the same CP-parity. These types of signals are very easy to detect experimentally. The corresponding CP-violating decay rate for the final states f_1 and f_2 is

$$\Gamma_{f_1 f_2} = \frac{1}{2R_m^2} \left[(2 + x^2 - y^2) |\lambda_{f_1} - \lambda_{f_2}|^2 + (x^2 + y^2) |1 - \lambda_{f_1} \lambda_{f_2}|^2 \right] \Gamma_{f_1} \Gamma_{f_2}. \quad (8)$$

The result of Eq. (8) represents a slight generalization of the formula given in Ref. [5]. It is clear that both terms in the numerator of Eq. (8) receive contributions from CP-violation of the type I and III, while the second term is also sensitive to CP-violation of the type II. Moreover, for a large set of the final states the first term would be additionally suppressed by $SU(3)_F$ symmetry, as for instance, $\lambda_{\pi\pi} = \lambda_{KK}$ in the $SU(3)_F$ symmetry limit. This expression is of the *second* order in CP-violating parameters (it is easy to see that in the approximation where only CP violation in the mixing matrix is retained, $\Gamma_{f_1 f_2} \propto |1 - R_m^2|^2 \propto A_m^2$).

The existing experimental constraints [6] demonstrate that CP-violating parameters are quite small in the charm sector, regardless of whether they are produced by the Standard Model mechanisms or by some new physics contributions. Since the above measurements involve CP-violating decay *rates*, these observables are of *second order* in the small CP-violating parameters, a challenging measurement.

b. CP-violation in decay asymmetries.

Most of the experimental techniques that are sensitive to CP violation make use of decay asymmetries, which are similar to the ones employed in B-physics [1],

$$a_f = \frac{\Gamma(D \rightarrow f) - \Gamma(\overline{D} \rightarrow \overline{f})}{\Gamma(D \rightarrow f) + \Gamma(\overline{D} \rightarrow \overline{f})}. \quad (9)$$

One can also introduce a related asymmetry,

$$a_{\overline{f}} = \frac{\Gamma(D \rightarrow \overline{f}) - \Gamma(\overline{D} \rightarrow f)}{\Gamma(D \rightarrow \overline{f}) + \Gamma(\overline{D} \rightarrow f)}. \quad (10)$$

Table I Current experimental constraints on CP-violating asymmetries in charged D -decays [6].

Decay mode	CP asymmetry
$D^+ \rightarrow K_S \pi^+$	-0.016 ± 0.017
$D^+ \rightarrow K_S K^+$	$+0.071 \pm 0.062$
$D^+ \rightarrow K^+ K^- \pi^+$	$+0.007 \pm 0.008$
$D^+ \rightarrow \pi^+ \pi^- \pi^+$	-0.017 ± 0.042
$D^+ \rightarrow K_S K^+ \pi^+ \pi^-$	-0.042 ± 0.068

For charged D -decays the only contribution to the asymmetry of Eq. (9) comes from the multi-component structure of the $\Delta C = 1$ decay amplitude of Eq. (2). In this case,

$$a_f = \frac{2Im(A_1 A_2^*) \sin \delta}{|A_1|^2 + |A_2|^2 + 2ReA_1 A_2^* \cos \delta} = 2r_f \sin \phi \sin \delta, \quad (11)$$

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 [7], i.e. at the $\mathcal{O}(1\%)$ level. This is the level at which a_f is currently probed experimentally, as summarized in Table I. As follows from Eq. (11), 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 generated¹. Moreover, presence of NP amplitudes does not significantly change this conclusion [9]. On the other hand, singly-Cabibbo-suppressed decays ($A_f \sim \lambda^1$) readily have 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,

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0. \quad (12)$$

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, CP-violating asymmetry is expected to be at most $a_f \sim 10^{-3}$ in the Standard Model. Model-dependent estimates of this asymmetry exist and are consistent with this estimate [10].

¹Technically, there is a small, $\mathcal{O}(\lambda^4)$ phase difference between the dominant tree T amplitude and exchange E amplitudes [8].

Asymmetries of Eq. (9) 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 [7, 11],

$$\begin{aligned} a_f &= a_f^d + a_f^m + a_f^i, \\ a_f^d &= 2r_f \sin \phi \sin \delta, \\ a_f^m &= -R_f \frac{y'}{2} (R_m - R_m^{-1}) \cos \phi, \\ a_f^i &= R_f \frac{x'}{2} (R_m + R_m^{-1}) \sin \phi, \end{aligned} \quad (13)$$

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, $f = \bar{f}$ and $y' = y$.

As can be seen from Eq. (13), the CP-violating asymmetries in neutral D -decays depend on $D^0 - \bar{D}^0$ mixing parameters x' and y' . Presently, experimental information about the $D^0 - \bar{D}^0$ mixing parameters x and y comes from the time-dependent analyses that can roughly be divided into two categories. First, more traditional studies look at the time dependence of $D \rightarrow f$ decays, where f is the final state that can be used to tag the flavor of the decayed meson. The most popular is the non-leptonic doubly Cabibbo suppressed decay $D^0 \rightarrow K^+ \pi^-$. Time-dependent studies allow one to separate the DCS from the mixing contribution $D^0 \rightarrow \bar{D}^0 \rightarrow K^+ \pi^-$,

$$\begin{aligned} \Gamma[D^0 \rightarrow K^+ \pi^-] &= e^{-\Gamma t} |A_{K^+ \pi^-}|^2 \\ &\left[R + \sqrt{R} R_m (y' \cos \phi - x' \sin \phi) \Gamma t \right. \\ &\quad \left. + \frac{R_m^2}{4} (y^2 + x^2) (\Gamma t)^2 \right], \end{aligned} \quad (14)$$

where R is the ratio of DCS and Cabibbo favored (CF) decay rates. Since x and y are small, the best constraint comes from the linear terms in t that are also *linear* in x and y . A direct extraction of x and y from Eq. (14) is not possible due to unknown relative strong phase δ_D of DCS and CF amplitudes [12], as $x' = x \cos \delta_D + y \sin \delta_D$, $y' = y \cos \delta_D - x \sin \delta_D$. This phase can be measured independently [13]. The corresponding formula can also be written [11] for \bar{D}^0 decay with $x' \rightarrow -x'$ and $R_m \rightarrow R_m^{-1}$.

Second, D^0 mixing can be measured by comparing the lifetimes extracted from the analysis of D decays into the CP-even and CP-odd final states. This study is also sensitive to a *linear* function of y via

$$\frac{\tau(D \rightarrow K^- \pi^+)}{\tau(D \rightarrow K^+ K^-)} - 1 = y \cos \phi - x \sin \phi \left[\frac{R_m^2 - 1}{2} \right]. \quad (15)$$

Time-integrated studies of the semileptonic transitions are sensitive to the *quadratic* form $x^2 + y^2$ and

Table II Current experimental constraints on CP-violating asymmetries in neutral D -decays [6].

Decay mode	CP asymmetry
$D^0 \rightarrow K^+ K^-$	$+0.0136 \pm 0.012$
$D^0 \rightarrow K_S K_S$	-0.23 ± 0.19
$D^0 \rightarrow \pi^+ \pi^-$	$+0.0127 \pm 0.0125$
$D^0 \rightarrow \pi^0 \pi^0$	$+0.001 \pm 0.048$
$D^0 \rightarrow \pi^+ \pi^- \pi^0$	$+0.01 \pm 0.09$
$D^0 \rightarrow K_S \pi^0$	$+0.001 \pm 0.013$
$D^0 \rightarrow K^- \pi^+ \pi^0$	-0.031 ± 0.086
$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$	-0.082 ± 0.073

at the moment are not competitive with the analyses discussed above.

Three experimental collaborations (BaBar, Belle and CDF) have recently announced evidence for observation of $D^0 - \bar{D}^0$ mixing [14] using the analyses described above. The results reported by these collaborations were combined by the Heavy Flavor Averaging Group (HFAG) to yield [6]

$$\begin{aligned} x &= (8.4_{-3.4}^{+3.2}) \times 10^{-3}, \\ y &= (6.9 \pm 2.1) \times 10^{-3}. \end{aligned} \quad (16)$$

Once again, it can be seen that the results depend on hadronic parameters, such as the strong phase δ_D . While the observed values of x and y , which are believed to be dominated by the Standard Model contributions (for recent analyses of NP contributions see [15]) and happen to be quite large, the SM CP-violating phases are still quite small. Thus, one can talk about almost background-free search for CP-violation induced by BSM interactions. Current experimental constraints on CP-violating asymmetries in neutral D -decays are summarized in Table II. As one can see, most measurements are the percent sensitivity. One should note that the rate asymmetries of Eq. (9) for neutral D -mesons require tagging of the initial state with the consequent reduction of the available dataset.

One question that can be asked is what models of New Physics can be probed via CP-violating observables in D -decays in the near future. A decomposition of Eq. (13) allows to address this question by studying parameters that enter Eq. (13). In particular, one needs to study the amplitude ratio r_f to see the feasibility of constraining a given NP model via charge asymmetries in D -decays. A general conclusion of the recent study [7] is that $\mathcal{O}(1\%)$ asymmetries are possible for SUSY models where new contributions come from QCD penguin operators and especially from chromomagnetic dipole operators, while tree-level direct CP violation in various known models is constrained to be much smaller than 10^{-2} (see

Table III Tree-level NP contributions to r_f [7].

Model	r_f
Extra quarks in vector-like rep	$< 10^{-3}$
R-parity violating SUSY	$< 1.5 \times 10^{-4}$
Two-Higgs doublet	$< 4 \times 10^{-4}$

Table III). Clearly, neutral D decays could exhibit contributions from indirect or direct CP violation (or both). One can experimentally distinguish between these possibilities [7] by selecting particular combinations of final states. For instance, combined analysis of $D \rightarrow K\pi$ and $D \rightarrow KK$ can yield interesting constraints on CP-violating parameters, which are universal [11],

$$\begin{aligned} \Delta Y_{KK} &= \frac{\Gamma'(D^0 \rightarrow K^+ K^-) - \Gamma'(\bar{D}^0 \rightarrow K^+ K^-)}{\Gamma'(D^0 \rightarrow K^+ K^-) + \Gamma'(\bar{D}^0 \rightarrow K^+ K^-)} \\ &= a_{KK}^m + a_{KK}^i, \end{aligned} \quad (17)$$

where $\Gamma'(D^0 \rightarrow K^+ K^-)$ and $\Gamma'(\bar{D}^0 \rightarrow K^+ K^-)$ are the modified decay rate parameters [11]

$$\begin{aligned} \Gamma'(D^0 \rightarrow K^+ K^-) &= \Gamma_D (1 \\ &\quad + \eta_f^{CP} R_m (y \cos \phi - x \sin \phi)), \\ \Gamma'(\bar{D}^0 \rightarrow K^+ K^-) &= \Gamma_D (1 \\ &\quad + \eta_f^{CP} R_m^{-1} (y \cos \phi + x \sin \phi)). \end{aligned} \quad (18)$$

Here $\eta_f^{CP} = +(-)$ for CP even (odd) states. The current experimental world average is $\Delta Y = (-0.35 \pm 0.47) \times 10^{-2}$, which gives a direct probe of CP-violating asymmetries related to mixing.

c. CP-violation with untagged samples.

It is possible to use a method that both does not require flavor or CP-tagging of the initial state and results in the observable that is *first order* in CP violating parameters [16]. Let's concentrate on the decays of D -mesons to final states that are common for D^0 and \bar{D}^0 . If the initial state is not tagged the quantities that one can easily measure are the sums

$$\Sigma_i = \Gamma_i(t) + \bar{\Gamma}_i(t) \quad (19)$$

for $i = f$ and \bar{f} . A CP-odd observable which can be formed out of Σ_i is the asymmetry

$$A_{CP}^U(f, t) = \frac{\Sigma_f - \Sigma_{\bar{f}}}{\Sigma_f + \Sigma_{\bar{f}}} \equiv \frac{N(t)}{D(t)}. \quad (20)$$

We shall consider both time-dependent and time-integrated versions of the asymmetry (20). Note that this asymmetry does not require quantum coherence of the initial state and therefore is accessible in any D -physics experiment. It is expected that the numerator

and denominator of Eq. (20) would have the form,

$$\begin{aligned} N(t) &= \Sigma_f - \Sigma_{\bar{f}} = e^{-\mathcal{T}} [A + BT + C\mathcal{T}^2], \\ D(t) &= 2e^{-\mathcal{T}} \left[|A_f|^2 + |A_{\bar{f}}|^2 \right], \end{aligned} \quad (21)$$

where we neglected direct CP violation in $D(t)$. Integrating the numerator and denominator of Eq. (20) over time yields

$$A_{CP}^U(f) = \frac{1}{D} [A + B + 2C], \quad (22)$$

where $D = \Gamma \int_0^\infty dt D(t)$.

Both time-dependent and time-integrated asymmetries depend on the same parameters A , B , and C . The result is

$$\begin{aligned} A &= |A_f|^2 - |\bar{A}_{\bar{f}}|^2 - |A_{\bar{f}}|^2 + |\bar{A}_f|^2, \\ B &= -2y\sqrt{R} \left[\sin\phi \sin\delta \left(|\bar{A}_f|^2 + |A_{\bar{f}}|^2 \right) \right. \\ &\quad \left. - \cos\phi \cos\delta \left(|\bar{A}_f|^2 - |A_{\bar{f}}|^2 \right) \right], \\ C &= \frac{x^2}{2} A. \end{aligned} \quad (23)$$

We neglect small corrections of the order of $\mathcal{O}(A_m x, r_f x, \dots)$ and higher. It follows that Eq. (23) receives contributions from both direct and indirect CP-violating amplitudes. Those contributions have different time dependence and can be separated either by time-dependent analysis of Eq. (20) or by the “designer” choice of the final state. Note that this asymmetry is manifestly *first* order in CP-violating parameters.

In Eq. (23), non-zero value of the coefficient A is an indication of direct CP violation. This term is important for singly Cabibbo suppressed (SCS) decays. The coefficient B gives a combination of a contribution of CP violation in the interference of the decays with and without mixing (first term) and direct CP violation (second term). Those contributions can be separated by considering DCS decays, such as $D \rightarrow K^{(*)}\pi$ or $D \rightarrow K^{(*)}\rho$, where direct CP violation is not expected to enter. The coefficient C represents a contribution of CP-violation in the decay amplitudes after mixing. It is negligibly small in the SM and all models of new physics constrained by the experimental data. Note that the effect of CP-violation in the mixing matrix on A , B , and C is always subleading.

Eq. (23) is completely general and is true for both DCS and SCS transitions. Neglecting direct CP violation we obtain a much simpler expression,

$$\begin{aligned} A &= 0, \quad C = 0, \\ B &= -2y \sin\delta \sin\phi \sqrt{R} \left[|\bar{A}_f|^2 + |A_{\bar{f}}|^2 \right]. \end{aligned} \quad (24)$$

For an experimentally interesting DCS decay $D^0 \rightarrow K^+\pi^-$ this asymmetry is zero in the flavor $SU(3)_F$ symmetry limit, where $\delta = 0$ [17]. Since $SU(3)_F$ is badly broken in D -decays, large values of $\sin\delta$ [12] are possible. At any rate, regardless of the theoretical estimates, this strong phase could be measured at CLEO-c. It is also easy to obtain the time-integrated asymmetry for $K\pi$. Neglecting small sub-leading terms of $\mathcal{O}(\lambda^4)$ in both numerator and denominator we obtain

$$A_{CP}^U(K\pi) = -y \sin\delta \sin\phi \sqrt{R}. \quad (25)$$

It is important to note that both time-dependent and time-integrated asymmetries of Eqs. (24) and (25) are independent of predictions of hadronic parameters, as both δ and R are experimentally determined quantities and could be used for model-independent extraction of CP-violating phase ϕ . Assuming $R \sim 0.4\%$ and $\delta \sim 40^\circ$ [12] and $y \sim 1\%$ one obtains $|A_{CP}^U(K\pi)| \sim (0.04\%) \sin\phi$. Thus, one possible challenge of the analysis of the asymmetry Eq. (25), is that it involves a difference of two large rates, $\Sigma_{K^+\pi^-}$ and $\Sigma_{K^-\pi^+}$, which should be measured with the sufficient precision to be sensitive to A_{CP}^U , a problem tackled in determinations of tagged asymmetries in $D \rightarrow K\pi$ transitions.

Alternatively, one can study SCS modes, where $R \sim 1$, so the resulting asymmetry could be $\mathcal{O}(1\%) \sin\phi$. However, the final states must be chosen such that A_{CP}^U is not trivially zero. For example, decays of D into the final states that are CP-eigenstates would result in zero asymmetry (as $\Gamma_f = \Gamma_{\bar{f}}$ for those final states) while decays to final states like K^+K^{*-} or $\rho^+\pi^-$ would not. It is also likely that this asymmetry is larger than the estimate given above due to contributions from direct CP-violation (see eq. 23). The final state f can also be a multiparticle state. In that case, more untagged CP-violating observables could be constructed, for instance involving asymmetries of the Dalitz plots, such as the ones proposed for B-decays [18].

As any rate asymmetry, Eq. (20) requires either a “symmetric” production of D^0 and \bar{D}^0 , a condition which is automatically satisfied by all $p\bar{p}$ and e^+e^- colliders, or a correction for D^0/\bar{D}^0 production asymmetry.

3. CP-violation in baryons

Charmed baryons provide another system for searches for CP-violation in charm. The fact that baryons are spin-1/2 particles allows us to form CP-violating asymmetries that are different from the ones in the meson systems.

Taking Λ_c as an example, a charmed baryon decay

amplitude can be parameterized as

$$\mathcal{A}(\Lambda_c \rightarrow B\pi) = \bar{u}_B(p, s) [A_S + A_P \gamma_5] u_{\Lambda_c}(p_\Lambda, s_\Lambda), \quad (26)$$

where B is a charmless baryon, and A_S and A_P parameterize s - and p -wave decay amplitudes respectively. They can be combined in an ‘‘asymmetry parameter’’ α_{Λ_c} as

$$\alpha_{\Lambda_c} = \frac{2\text{Re}(A_S^* A_P)}{|A_S|^2 + |A_P|^2}. \quad (27)$$

This parameter can be directly measured experimentally using angular distribution of decay products in Λ_c decay,

$$\frac{dW}{d\theta} = \frac{1}{2}(1 + P\alpha_{\Lambda_c} \cos\theta). \quad (28)$$

Here P is polarization of the initial-state baryon. If this analysis can be done for $\bar{\Lambda}_c$ decay as well, then a CP-violating asymmetry can be formed,

$$\mathcal{A}_f = \frac{\alpha_{\Lambda_c} + \alpha_{\bar{\Lambda}_c}}{\alpha_{\Lambda_c} - \alpha_{\bar{\Lambda}_c}}, \quad (29)$$

which follows from the fact that $\alpha_{\Lambda_c} \rightarrow -\alpha_{\bar{\Lambda}_c}$ under CP-transformation (if CP is conserved).

There were some experimental studies of this observable. In particular, FOCUS collaboration reported [19]

$$\mathcal{A}_{\Lambda\pi} = -0.07 \pm 0.19 \pm 0.24. \quad (30)$$

New studies of CP-asymmetries in charmed baryon decays are urged, which could be performed at LHCb or even in one of the new experiments associated with Project-X at FNAL [20].

4. Conclusions

In summary, charm physics, and in particular studies of CP-violation, could provide new and unique opportunities for indirect searches for New Physics. Large statistical samples of charm data allow unique sensitive measurements of charm mixing and CP-violating parameters. While unambiguous theoretical predictions of CP-violating asymmetries in charm transitions are hard, observation of CP-violation at the level of $\mathcal{O}(1\%)$ would indicate new physics contribution to charm decays.

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References

- [1] I. I. Bigi and A. I. Sanda, *CP violation* (Cambridge University Press, 2000).
- [2] E. Golowich, ‘‘Charm Mixing - Theory,’’ these proceedings, arXiv:0710.0151 [hep-ph].
- [3] A. F. Falk, Y. Grossman, Z. Ligeti and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002); A. F. Falk, Y. Grossman, Z. Ligeti, Y. Nir and A. A. Petrov, Phys. Rev. D **69**, 114021 (2004). For earlier estimates see A. Datta, D. Kumbhakar, Z. Phys. C**27**, 515 (1985); A. A. Petrov, Phys. Rev. D**56**, 1685 (1997); E. Golowich and A. A. Petrov, Phys. Lett. B **427**, 172 (1998). E. Golowich and A. A. Petrov, Phys. Lett. B **625**, 53 (2005) [arXiv:hep-ph/0506185]. H. Georgi, Phys. Lett. B**297**, 353 (1992); T. Ohl, G. Ricciardi and E. Simmons, Nucl. Phys. B**403**, 605 (1993); I. Bigi and N. Uraltsev, Nucl. Phys. B **592**, 92 (2001). J. Donoghue, E. Golowich, B. Holstein and J. Trampetic, Phys. Rev. D**33**, 179 (1986); L. Wolfenstein, Phys. Lett. B**164**, 170 (1985); P. Colangelo, G. Nardulli and N. Paver, Phys. Lett. B**242**, 71 (1990); T.A. Kaeding, Phys. Lett. B**357**, 151 (1995); A. A. Anselm and Y. I. Azimov, Phys. Lett. B **85**, 72 (1979).
- [4] S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7-8**, 1 (2003); G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431 (2003). A. A. Petrov, eConf **C030603**, MEC05 (2003) [arXiv:hep-ph/0311371]; H. N. Nelson, in *Proc. of the 19th Intl. Symp. on Photon and Lepton Interactions at High Energy LP99* ed. J.A. Jaros and M.E. Peskin, arXiv:hep-ex/9908021.
- [5] I. I. Bigi and A. I. Sanda, Phys. Lett. B **171**, 320 (1986).
- [6] B.A. Peterson, ‘‘HFAG Mixing Averages,’’ these proceedings; see also <http://www.slac.stanford.edu/xorg/hfag/charm/index.html>
- [7] Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D **75**, 036008 (2007) [arXiv:hep-ph/0609178].
- [8] A.A. Petrov, in *Proceedings of 1999 Meeting of the Division of Particles and Fields of the American Physical Society*, edited by Katsushi Arisaka and Zvi Bern, <http://www.dpf99.library.ucla.edu/session4/petrov0414.pdf>
- [9] S. Bergmann and Y. Nir, JHEP **9909**, 031 (1999) [arXiv:hep-ph/9909391].
- [10] F. Buccella, M. Lusignoli, G. Mangano, G. Miele, A. Pugliese and P. Santorelli, Phys. Lett. B **302**, 319 (1993) [arXiv:hep-ph/9212253].
- [11] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir, A. Petrov, Phys. Lett. B **486**, 418 (2000).
- [12] A. F. Falk, Y. Nir and A. A. Petrov, JHEP **9912**, 019 (1999); Z. z. Xing, Phys. Lett. B **372**, 317 (1996) [arXiv:hep-ph/9512216].
- [13] M. Gronau, Y. Grossman and J. L. Rosner, Phys. Lett. B **508**, 37 (2001).

- [14] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007) [arXiv:hep-ex/0703020]; M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007) [arXiv:hep-ex/0703036]; The CDF collaboration, Public Note 07-08-09 (unpublished).
- [15] E. Golowich, J. Hewett, S. Pakvasa and A. A. Petrov, arXiv:0705.3650 [hep-ph]; E. Golowich, S. Pakvasa and A. A. Petrov, Phys. Rev. Lett. **98**, 181801 (2007) [arXiv:hep-ph/0610039]; A. A. Petrov and G. K. Yeghiyan, arXiv:0710.4939 [hep-ph].
- [16] A. A. Petrov, Phys. Rev. D **69**, 111901 (2004).
- [17] L. Wolfenstein, Phys. Lett. B **164**, 170 (1985).
- [18] S. Gardner and J. Tandean, Phys. Rev. D **69**, 034011 (2004) [arXiv:hep-ph/0308228].
- [19] J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **634**, 165 (2006) [arXiv:hep-ex/0509042].
- [20] D. M. Kaplan, arXiv:0707.1917 [hep-ex].