Hunting for CP violation with untagged charm decays

Alexey A. Petrov

Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201 and Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109

We construct a CP-violating observable which does not require flavor or CP tagging of the initial state. The proposed decay asymmetry could be measured at both threshold and non-threshold charm physics experiments and provide better sensitivity to small CP-violating parameters in charm decays.

I. INTRODUCTION

One of the most important motivations for studies of CP violation in charm decays is the possibility of observing signals of new physics. It is expected that CP-violating amplitudes generated by Standard Model (SM) interactions are numerically small \[1\], so observation of CP-violation in the current round of experiments will provide a “smoking gun” signal of new physics, even if its source is not clearly identified. This robust prediction follows from the fact that weak decay of the charmed meson or baryon is governed by the real $2 \times 2$ Cabbibo matrix, as all quarks which build up the hadronic states in non-leptonic weak decay belong to the first two generations. The only possible SM CP-violating amplitude comes from the virtual $b$ quarks in penguin or box-type diagrams, but it is strongly suppressed by the small combination of Cabbibo-Kobayashi-Maskawa (CKM) matrix elements $V_{cb}^* V_{ub} \sim O(\lambda^5)$, where $\lambda = 0.2$ is the Wolfenstein parameter. This small “Standard Model background” makes charm decays a valuable tool in searching for CP-violating effects of new physics, especially since the acquired datasets available in charm physics experiments are usually quite large.

Let us first review the relevant formalism in order to collect necessary formulas. As in B-decays, CP violating contributions can affect charm transitions in three distinct ways \[2\].

(1) CP violation can affect $D$ decay amplitudes. This type of CP violation (also called “direct CP-violation”) occurs when the absolute value of the decay amplitude $|A_f|$ for $D$ to decay to a final state $f$ is different from the one of corresponding CP-conjugated amplitude, i.e. $|A_f| \neq |\bar{A}_f|$. This type of CP violation occurs in both charged and neutral $D$-decays and is induced by $\Delta C = 1$ effective operators. The easiest way of observing it is by examining the rate asymmetries,

\[
A_{CP}(f) = \frac{\Gamma_f - \bar{\Gamma}_f}{\Gamma_f + \bar{\Gamma}_f} = 1 - \frac{|\bar{A}_f/A_f|^2}{1 + |\bar{A}_f/A_f|^2}, \tag{1}
\]

where $\Gamma_i$ represents the $D^0 \to i$ decay rate, while $\bar{\Gamma}_i$ represents the $\bar{D}^0 \to i$ rate. A two-component decay amplitude with weak and strong phase differences is required for this type of CP violation,

\[
A_f = A_f \left[ 1 + r_f e^{i(\Delta_f + \theta)} \right]. \tag{2}
\]

Here $\Delta_f$ corresponds to the strong phase difference and $\theta$ corresponds to the weak phase difference between the CP-conserving ($A_f$) and CP-violating parts of the decay amplitude and $r_f$ represents the (small) ratio of their absolute values. Note that Eq. (2) is a scale and scheme-independent way to write a non-leptonic decay amplitude. While no reliable model-independent predictions exist for the $\Delta_f$, it is believed that it could be quite large due to the abundance of light-quark resonances in the vicinity of the $D$-meson mass inducing large final-state interaction (FSI) phases. As the most optimistic model-dependent estimates put the Standard Model predictions for the asymmetry $A_{CP} < 0.1\%$, an observation of any CP-violating signal in the current round of experiments will be a sign of new physics. Current FOCUS, CLEO, and Belle/BaBar results put rather stringent bounds on $A_{CP}$. For example, for a state $K^+ K^-$ the direct CP asymmetry is \[3\]

\[
A_{CP}(K^+ K^-) = (0.0 \pm 2.2 \pm 0.8)\%. \tag{3}
\]
Searches for this type of CP-violation in neutral charm decays must deal with the tagged data sample, which means that only $D$-mesons tagged at production, typically in $D^* \to D^0 \pi$ decay, could be used in this analysis. This imposes restrictions on the available dataset of $D$'s which could be used for this analysis.

(2) CP violation can affect the $D^0 - \bar{D}^0$ mixing matrix. This type of CP violation occurs when effective operators that change $D^0$ into $\bar{D}^0$ states, i.e. generate the mass and width splittings for the mass eigenstates of the $D^0 - \bar{D}^0$ system, have CP-violating coefficients. This results in the mixing of flavor eigenstates into the mass eigenstates,

$$|D_j\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle.$$  (4)

Here the complex parameters $p$ and $q$ are the off-diagonal elements in the phenomenological parametrization of the $D^0 - \bar{D}^0$ mass matrix\cite{5}.

$$\begin{bmatrix} M - i\frac{\Gamma}{2} \end{bmatrix}_{ij} = \begin{pmatrix} A & p^2 \\ q^2 & A \end{pmatrix}. \quad (5)$$

CP violation in the mixing matrix occurs when

$$R_{m}^{2} = \frac{|q|^2}{|p|^2} = \frac{2M_{\pi}^2 - i\Gamma_{\pi}^2}{2M_{D_{L}} - i\Gamma_{D_{L}}^2} \neq 1. \quad (6)$$

It is convenient to define two dimensionless variables $x$ and $y$ which are the normalized mass and width differences of $D_1$ and $D_2$,

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

where $m_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the corresponding mass eigenstates, i.e. the eigenvalues of the mixing matrix in Eq. (5) and $\Gamma = (\Gamma_1 + \Gamma_2) / 2$.

This type of CP violation in charm can be observed most cleanly by looking for semileptonic decay asymmetries $A_{SL}$, like the one in Eq. (11) with $f = X\ell\nu$. It is easy to see that $A_{SL} = (1 - R_{m}^2)/(1 + R_{m}^2)$\cite{2}. This asymmetry is expected to be tiny in both the SM and many of its extensions.

(3) CP violation can occur 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 $\bar{D}^0$ can decay. It is usually associated with the relative phase between mixing and decay contributions. It can be studied by examining the time-dependent version of rate asymmetry $A_{CP}(f)$ of Eq. (11).

Studies of $D^0 - \bar{D}^0$ oscillations offer a convenient probe of CP violation in the charm system. Using the notations of\cite{6}, let us write the time-dependent decay rates of $D^0$ and $\bar{D}^0$ to a given final state $f$. Since $x, y \ll 1$\cite{6,8} and denoting $T = \Gamma t$,

$$\Gamma_f(t) = \frac{R_{m}^2}{|A_f|^2} e^{-T} \left[ |\lambda_f^{-1}|^2 + \left[ \text{Re} \left( \lambda_f^{-1} \right) y + \text{Im} \left( \lambda_f^{-1} \right) x \right] T + \left[ (x^2 + y^2) - (x^2 - y^2) |\lambda_f^{-1}|^2 \right] \frac{T^2}{4} \right],$$

$$\bar{\Gamma}_f(t) = \frac{R_{m}^2}{|\bar{A}_f|^2} e^{-T} \left[ |\lambda_f|^{-2} + \left[ \text{Re} (\lambda_f) y + \text{Im} (\lambda_f) x \right] T + \left[ (x^2 + y^2) - (x^2 - y^2) |\lambda_f|^2 \right] \frac{T^2}{4} \right], \quad (8)$$

where for a given final state $f$, CP violation is parametrized by

$$\lambda_f^{-1} = \frac{p}{q} \frac{A_f}{\bar{A}_f} = \sqrt{R} R_{m} e^{-i(\delta + \phi)} + O(r_f),$$

$$\lambda_T = \frac{q}{p} \frac{\bar{A}_f}{A_f} = \sqrt{R} R_{m} e^{-i(\delta - \phi)} + O(r_T), \quad (9)$$

where $A_f$ and $\bar{A}_f$ are the amplitudes for $D^0 \to f$ and $\bar{D}^0 \to f$ transitions respectively, $\delta$ is the strong phase difference between $A_f$ and $\bar{A}_f$, and $R = |A_f/\bar{A}_f|^2$. Here $\phi$ represents the convention-independent CP-violating weak phase difference between the ratio of decay amplitudes and the mixing matrix. The corresponding expressions for $\Gamma_f(t)$ and $\bar{\Gamma}_f(t)$ can be found by substituting $f \to \bar{f}$ in Eqs. (8).

Eqs. (8) give the most general expression for time-dependent decay rate up to $O(x^2, y^2)$. However, parameters of these equations (i.e. coefficients of $x$ and $y$ to the appropriate power) scale differently for singly Cabbibo suppressed (SCS)
or doubly Cabbibo suppressed (DCS) decays. For instance, \( R \sim O(\lambda^2) \) for DCS decays like \( D^0 \rightarrow K^+\pi^- \), while \( R \sim O(1) \) for SCS transitions such as \( D^0 \rightarrow \pi^+\rho^- \). This implies that in the studies of a particular DCS or SCS transition, some of the terms in Eqs. (8) could be neglected. CP-violating parameters could be extracted by comparing the time-dependent rates of \( D^0 \) and \( \bar{D}^0 \) decays in Eq. (3).

II. UNTAGGED SIGNALS OF CP VIOLATION

The existing experimental constraints [4] 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. In that respect, it is important to maximally exploit the available statistics. It is easy to see that the rate asymmetries of Eq. (1) require tagging of the initial state with the consequent reduction of the dataset.

Another way of looking for CP-violation involves methods which are being discussed in connection with CLEO-c tau-charm factory measurements. They do not require initial state flavor tagging but rely on the fact that at the threshold charm factory initial \( D^0 - \bar{D}^0 \) state is prepared in the state with definite CP. An observation of a final state of the opposite CP would automatically imply CP-violation. These signals were discussed in [5]. Since they involve CP-violating decay rates, these observables are of second order in the small CP-violating parameters, a challenging measurement.

We propose 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. 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

\[
\Sigma_i = \Gamma_i(t) + \bar{\Gamma}_i(t) \tag{10}
\]

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

\[
A^U_{CP}(f, t) = \frac{\Sigma_f - \Sigma_{\bar{f}}}{\Sigma_f + \Sigma_{\bar{f}}} \equiv \frac{N(t)}{D(t)}. \tag{11}
\]

We shall consider both time-dependent and time-integrated versions of the asymmetry [11]. Note that this asymmetry does not require quantum coherence of the initial state and therefore is accessible in any D-physics experiment. From Eq. (11) it is expected that the numerator and denominator of Eq. (11) would have the form,

\[
N(t)=\Sigma_f - \Sigma_{\bar{f}} = e^{-T} [A + BT + C T^2],
\]

\[
D(t)= e^{-T} \left[ |A_f|^2 + |\bar{A}_f|^2 + |A_{\bar{f}}|^2 + |\bar{A}_{\bar{f}}|^2 \right]. \tag{12}
\]

Integrating the numerator and denominator of Eq. (11) over time yields

\[
A^U_{CP}(f) = \frac{1}{D} [A + B + 2C], \tag{13}
\]

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

Both time-dependent and time-integrated asymmetries depend on the same parameters \( A, B, \) and \( C \). Since CP-violation in the mixing matrix is expected to be small, we follow [12] and expand \( R_m^{\pm2} = 1 \pm A_m \). The result is

\[
A = \left( |A_f|^2 - |\bar{A}_f|^2 \right) - \left( |A_{\bar{f}}|^2 - |\bar{A}_{\bar{f}}|^2 \right) = |A_f|^2 \left[ 1 - \frac{|\bar{A}_f|^2}{|A_f|^2} \right] + R \left[ 1 - \frac{|A_{\bar{f}}|^2}{|\bar{A}_{\bar{f}}|^2} \right],
\]

\[
B = -2y\sqrt{R} \left[ \sin \phi \sin \delta \left( |A_{\bar{f}}|^2 + |A_f|^2 \right) - \cos \phi \cos \delta \left( |A_f|^2 - |A_{\bar{f}}|^2 \right) \right] + O(A_{mx, rf x, ...}), \tag{14}
\]

\[
C = \frac{y^2}{2} \left[ \left( |A_f|^2 - |\bar{A}_f|^2 \right) - \left( |A_{\bar{f}}|^2 - |\bar{A}_{\bar{f}}|^2 \right) \right] = \frac{y^2}{2} A + O(A_{mx, rf x, ...}).
\]

We neglect small corrections of the order of \( O(A_{mx, rf x, ...}) \) and higher. It follows that
Eq. (14) 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. (11) or by the “designer” choice of the final state. Note that this asymmetry is manifestly first order in CP-violating parameters.

In Eq. (14), non-zero value of the coefficient $A$ is an indication of direct CP violation. This term might be important for 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 $D \to K^{(*)}\pi$ or $D \to K^{(*)}\rho$, 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. (14) is completely general and is true for both DCS and SCS transitions. For an experimentally interesting DCS decay $D^0 \to K^{+}\pi^-$ we can neglect direct CP violation and obtain a much simpler expression,

$$ A = 0, \quad C = 0 $$

$$ B = -2y\sin\delta\sin\phi\sqrt{R} |A_{K^{+}\pi^-}|^2. \quad (15) $$

This asymmetry is zero in the flavor $SU(3)_F$ symmetry limit, where $\delta = 0$. Since $SU(3)_F$ is badly broken in $D$-decays, large values of $\sin\delta$ 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 subleading terms of $O(\lambda^4)$ in both numerator and denominator we obtain

$$ A_{CP}(K\pi) = -y\sin\delta\sin\phi\sqrt{R}. \quad (16) $$

It is important to note that both time-dependent and time-integrated asymmetries of Eqs. (15) and (16) are independent of predictions of hadronic parameters, as both $\delta$ and $R$ are experimentally determined quantities and could be used for model-independent extraction of CP-violating phase $\phi$. Assuming $R \sim 0.4\%$ and $\delta \sim 40^\circ$ and $y \sim 1\%$ one obtains $|A_{CP}(K\pi)| \sim (0.04\%)\sin\phi$. Thus, one possible challenge of the analysis of the asymmetry Eq. (11) 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 $A_{CP}$, a problem tackled in determinations of tagged asymmetries in $D \to K\pi$ transitions.

Alternatively, one can study SCS modes, where $R \sim 1$, so the resulting asymmetry could be $O(1\%)\sin\phi$. However, the final states must be chosen such that $A_{CP}$ is not trivially zero. For example, decays of $D$ into the final states that are CP-eigenstates would result in zero asymmetry (as $\Gamma_f = \Gamma_T$ for those final states) while decays to final states like $K^+K^-$ or $\rho^+\pi^-$ would not.

The final state $f$ can also be a multiparticle state. In that case, more untagged CP-violating observables could be constructed. For instance, three body decays can exhibit CP-violating Dalitz plot asymmetries, like the $E_+ \leftrightarrow E_-$ asymmetry of the Dalitz plot in the decay $D \to K_S\pi^+\pi^-(E_+)\pi^-(E_-)$. Similar studies of Dalitz plot asymmetries in $B_d$-decays were suggested in \cite{13}.

Untagged studies of Dalitz plot population asymmetries resulting from the Jacobi-constraints intermediate states were proposed in \cite{14} to study direct CP-violation in $B_d$ decays. The use of untagged samples were also proposed to measure $\Delta\Gamma$ and CKM phase $\gamma$ in $B_s$ decays \cite{13}, where large values of $x_s$ cause these terms to oscillate rapidly and, effectively to cancel out for sufficiently large $t$. The situation in charm transitions is exactly opposite.

As any rate asymmetry, Eq. (11) requires either a “symmetric” production of $D^0$ and $\overline{D^0}$, a condition which is automatically satisfied by all $p\overline{p}$ and $e^+e^-$ colliders, or a correction for $D^0/\overline{D^0}$ production asymmetry.

### III. CONCLUSIONS

We propose a method of searching for CP-violation in charm decays which does not require either flavor or CP tagging of the initial state. The resulting asymmetry is first order in CP-violating parameters, which is important for charm transitions. The unique feature of the asymmetry of Eq. (11) is that, apart from the small CP-violating phase, it could be sizable even for two body final transitions.

\footnote{1} That study, however, neglected the contribution due to lifetime difference $y$ (which a good approximation in $B_d$ decays), leading for $D$-meson transitions.

\footnote{2} I thank Y. Grossman for pointing this reference to me.
states. This occurs because of the large $SU(3)_F$ symmetry breaking in charm transitions.

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[1] A. A. Petrov, arXiv:hep-ph/0311371; G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. 53, 431 (2003).
[2] For the concise review, see BaBar Physics Book or I. I. Y. Bigi and A. I. Sanda, “CP Violation,” Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol. 9, 1 (2000).
[3] F. Buccella, M. Lusignoli and A. Pugliese, Phys. Lett. B 379, 249 (1996).
[4] E. Csorna et al. [CLEO Collaboration], Phys. Rev. D 65, 092001 (2002); B. D. Yabsley, arXiv:hep-ex/0311057.
[5] See, for example, J. F. Donoghue, E. Golowich and B. R. Holstein, “Dynamics of the standard model,” Cambridge Univ. Press (1992).
[6] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir and A. A. Petrov, Phys. Lett. B 486, 418 (2000).
[7] A. Datta, D. Kumbhakar, Z. Phys. C27, 515 (1985); A. A. Petrov, Phys. Rev. D56, 1685 (1997); 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).
[8] E. Golowich and A. A. Petrov, Phys. Lett. B427, 172 (1998); 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, arXiv:hep-ph/0402204.
[9] I. I. Bigi and A. I. Sanda, Phys. Lett. B 171, 320 (1986).
[10] L. Wolfenstein, Phys. Lett. B 164, 170 (1985).
[11] A. F. Falk, Y. Nir and A. A. Petrov, JHEP 9912, 019 (1999).
[12] J. P. Silva and A. Soffer, Phys. Rev. D 61, 112001 (2000); M. Gronau, Y. Grossman and J. L. Rosner, Phys. Lett. B 508, 37 (2001).
[13] G. Burdman and J. F. Donoghue, Phys. Rev. D 45, 187 (1992).
[14] S. Gardner and J. Tandean, Phys. Rev. D 69, 034011 (2004); S. Gardner, Phys. Lett. B 553, 261 (2003).
[15] I. Dunietz, Phys. Rev. D 52, 3048 (1995); Y. Grossman, Phys. Lett. B 380, 99 (1996).