Direct CP violation in singly Cabibbo-suppressed D-meson decays

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Abstract

The LHCb and CDF collaborations reported a surprisingly large difference between the direct CP asymmetries, $\Delta A_{CP}$, in the $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$ decay modes. We show that this measurement can be plausibly explained within the standard model under the assumption of large penguin contractions matrix elements and nominal $U$-spin breaking. A consistent picture arises, accommodating the large difference between the decay rates, and the measured decay rates of the $D \to K\pi$ modes.

Proceedings of CKM 2012, the 7th International Workshop on the CKM Unitarity Triangle, University of Cincinnati, USA, 28 September - 2 October 2012

1 Introduction

The $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$ decays are induced by the weak interaction via an exchange of a virtual $W$ boson and are suppressed by a single power of the Cabibbo angle. Direct $CP$ violation in singly Cabibbo-suppressed (SCS) $D$-meson decays is sensitive to contributions of new physics in the up-quark sector, since it is expected to be small in the standard model: the $b$-quark penguin amplitudes necessary for interference are down by a loop factor and small Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, and there is no heavy virtual top quark which could provide substantial breaking of the Glashow-Iliopoulos-Maiani (GIM) mechanism. Naively, one would thus expect effects of order $\mathcal{O}([V_{cb} V_{ub}/V_{cs} V_{us}] \alpha_s/\pi) \sim 0.01\%$.

We define the amplitudes for final state $f$ as

$$A_f \equiv A(D \to f) = A_T^f [1 + r_f e^{i(\delta_f - \phi_f)}],$$

$$\bar{A}_f \equiv A(\bar{D} \to f) = A_T^f [1 + r_f e^{i(\delta_f + \phi_f)}].$$

(1)

Note that the possibility of $CP$ violation by tree amplitudes has already been pointed out in [1].
Here $A_T^f$ is the dominant tree amplitude and $r_f$ the relative magnitude of the sub-leading amplitude, carrying the weak phase $\phi_f$ and the strong phase $\delta_f$. We can now define the direct $CP$ asymmetry as

$$A_{\text{dir}}^f \equiv \frac{|A_f|^2 - |\overline{A}_f|^2}{|A_f|^2 + |\overline{A}_f|^2} = 2r_f \sin \gamma \sin \delta_f,$$  \hspace{1cm} (2)

where the last equality holds up to corrections of $O(r_f^2)$. LHCb and CDF measure a time-integrated $CP$ asymmetry. The approximately universal contribution of indirect $CP$ violation cancels to good approximation in the difference

$$\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-).$$  \hspace{1cm} (3)

The measurements of LHCb, $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$ [2], CDF, $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$ [3], lead to the new world average (including the Babar [4], Belle [5], and CDF [6] measurements) $\Delta A_{CP} = (-0.67 \pm 0.16)\%$ [3].

We show that the large difference of SCS branching ratios, $Br(D^0 \to K^+K^-) \approx 2.8 \times Br(D^0 \to \pi^+\pi^-)$, together with nominal $U$-spin breaking of $O(20\%)$, implies large penguin matrix elements, which in turn account for the large value of $\Delta A_{CP}$.

## 2 A consistent picture

The starting point of our analysis is the weak effective Hamiltonian

$$H_{\text{eff}}^{\text{SCS}} = \frac{G_F}{\sqrt{2}} \left\{ (V_{cs}V_{us}^* - V_{cd}V_{ud}^*) \sum_{i=1,2} C_i \left( Q_i^{zs} - Q_i^{zd} \right) / 2 ight. \right.

\left. - V_{cb}V_{ub}^* \left[ \sum_{i=1,2} C_i \left( Q_i^{zs} + Q_i^{zd} \right) / 2 + \sum_{i=3}^{6} C_i Q_i + C_{8g}Q_{8g} \right] \right\} + \text{h.c.} \hspace{1cm} (4)

The Wilson coefficients of the tree operators $Q_i^{\rho\rho'} = (\bar{p}u)_{V-A} \otimes (\bar{c}p')_{V-A}$, $Q_{8g}^{\rho\rho'} = (\bar{p}_a u_{\beta})_{V-A} \otimes (\bar{c}P'_{\alpha})_{V-A}$, the penguin operators $Q_{3...6}$, and the chromomagnetic operator $Q_{8g}$, can be calculated in perturbation theory [9]. The hadronic matrix elements are of nonperturbative nature and will ultimately can be computed using lattice QCD [10]. We will estimate their size using experimental data.

A leading power estimation of the ratio $r_{LP}^f \equiv |A_{LP}^f(\text{leading power})/A_{T}^f(\text{experiment})|$, using naive factorization and $O(\alpha_s)$ corrections, yields $r_{K^+K^-}^{LP} \approx (0.01 - 0.02)\%$, $r_{\pi^+\pi^-}^{LP} \approx (0.015 - 0.028)\%$ [11]. This is consistent with, yet slightly larger than the naive scaling estimate. We expect the signs of $A_{\text{dir}}^{K^+K^-}$ and $A_{\text{dir}}^{\pi^+\pi^-}$ to be opposite, if $SU(3)$ breaking is not too large; so for $\phi_f = \gamma \approx 67^\circ$ and $O(1)$ strong phases we
obtain $\Delta A_{CP}$ (leading power) $= \mathcal{O}(0.1\%)$, an order of magnitude smaller than the measurement. However, from $SU(3)$ fits \cite{12, 13, 14, 15, 16} we know that power corrections can be large. To be specific, we look at insertions of the penguin operators $Q_4, Q_6$ into power-suppressed annihilation amplitudes. The associated penguin contractions of $Q_4$ cancel the scale and scheme dependence. A rough estimate of their size leads to $r^{PC}_{f_i}(Q_4) \approx (0.04 \pm 0.08)\%$, $r^{PC}_{f_i}(Q_6) \approx (0.03 \pm 0.04)\%$, where $r^{PC}_{f_i}(Q_4) \equiv |A^{f_i}_P(\text{power correction})/A^{f_i}_P(\text{experiment})|$ for the insertion of $Q_4$, with an uncertainty of a factor of a few. Larger effects are very unlikely \cite{11}. Again assuming $\mathcal{O}(1)$ strong phases, this leads to $\Delta A_{CP}(r_{f,1}) = \mathcal{O}(0.3\%)$ and $\Delta A_{CP}(r_{f,2}) = \mathcal{O}(0.2\%)$ for the two insertions. Thus, a standard-model explanation seems plausible.

This conclusion receives further support from data. The large difference of SCS branching ratios translates into a ratio of amplitudes (normalized to phase space) of $A(D^0 \to K^+K^-) \approx 1.8 \times A(D^0 \to \pi^+\pi^-)$, whereas the amplitudes would be equal in the $SU(3)$ limit. This has often been interpreted as a sign of large $SU(3)$ breaking. On the other hand, the ratio of the Cabibbo-favored (CF) to the doubly Cabibbo-suppressed (DCS) amplitude is $A(D^0 \to K^-\pi^+) \approx 1.15 \times A(D^0 \to K^+\pi^-)$, after accounting for CKM factors, in accordance with nominal $SU(3)$ breaking of $\mathcal{O}(20\%)$. This value is affirmed by the fact that the experimental amplitudes satisfy the sum rule relation

$$\frac{|A(D^0 \to K^+K^-)| + |A(D^0 \to \pi^+\pi^-)|}{|A(D^0 \to K^-\pi^+)| + |A(D^0 \to K^+\pi^-)|} - 1 = (4.0 \pm 1.6)\%.$$  \hspace{1cm} (5)

This expression would vanish in the $U$-spin limit and receives correction quadratic in $U$-spin breaking.

An inspection of the effective Hamiltonian \cite{4} shows that the combination $P$ of penguin contractions of $Q_{1,2}^7$ and $Q_{1,2}^{3d}$ proportional to $V_{cb}V_{ub}^*$ is $U$-spin invariant, while $P_{\text{break}}$, the combination of penguin contractions contributing to the decay rates vanishes in the $U$-spin limit. $P_{\text{break}}$ contributes with opposite sign to the two SCS decay rates, and $P$ gives rise to a nonvanishing $\Delta A_{CP}$. Guided by the considerations above, we perform a $U$-spin decomposition of the amplitudes to all four (CF, SCS, DCS) decays, and fit these amplitudes to the data (branching ratios and $CP$ asymmetries) \cite{17}. There we also provide an exact definition of the amplitudes and a translation between the $U$-spin decomposition and the operator picture.

Our main point is that under the assumption of nominal $U$-spin breaking, a broken penguin $P_{\text{break}}$, which explains the difference of the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decay rates, implies a $\Delta U = 0$ penguin $P$ that naturally\footnote{An important side remark is that no fine tuning of strong phases is required \cite{17}.} yields the observed $\Delta A_{CP}$. The scaling $P_{\text{break}} \sim \epsilon_U P$ together with our fit to the branching ratios alone yields $P_{\text{break}} \sim T/2$ (see Fig.\cite{1}), leading to the estimate

$$r_{\pi^+\pi^-,K^+K^-} \approx \left|\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\right| \cdot \frac{P}{T \pm P_{\text{break}}} \approx \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|} \frac{1}{2\epsilon_U} \sim 0.2\%, \hspace{1cm} (6)$$
for $\epsilon_U \sim 0.2$. This is consistent with the measured $\Delta A_{CP}$ assuming $O(1)$ strong phases. A fit to the full data set including $CP$ asymmetries confirms this naive estimate (see Figure 1), showing that large penguin contraction matrix elements together with nominal $U$-spin breaking lead to a consistent picture accommodating all data on decay rates and $CP$ asymmetries of all four (CF, SCS, DCS) modes [17].

I thank Yuval Grossman, Alexander Kagan, and Jure Zupan for the pleasant and fruitful collaboration, and the organizers of the “CKM 2012 workshop” for the invitation to this inspiring conference. The work of J. B. is supported by DOE grant FG02-84-ER40153.

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