# Final state phases in $B \to D\pi$, $\overline{D}\pi$ decays and $CP$ asymmetry

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Final state phases $\delta_f$ and $\delta'_f$ in $B \to D\pi$, $\bar{D}\pi$ decays are shown to be equal, i.e., $\delta = \delta_f - \delta'_f = 0$. Thus $CP$-violating asymmetry $\mathcal{A}(t)$ is independent of final state phases. The estimate for the phases $\delta_f$ and $\delta'_f$ is also given.

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Time-dependent $B$-decays are a good source of our knowledge regarding $CP$-violation. However $CP$-violation involves final state phases. Thus it is not possible to extract the weak phase $\gamma$ without some knowledge of final state phases. $\Delta C = \pm 1$, $\Delta S = 0$ $B$-decays are of special interest, because for these decays, it is possible to show that final state phase $\delta = 0$. The purpose of this paper is to show that this is the case. It is convenient to write the time-dependent decay rates in the form (For a review, see, for example, Refs. [1–3])

$$\begin{aligned}\{\Gamma[B^0(t)\to f]-\Gamma[\bar{B}^0(t)\to \bar{f}]\}+\{\Gamma[B^0(t)\to \bar{f}]-\Gamma[\bar{B}^0(t)\to f]\} = e^{-\Gamma t}\{&\cos\Delta mt[(|\langle f|H|B^0\rangle|^2-|\langle \bar{f}|H|\bar{B}^0\rangle|^2)\\ &+(|\langle \bar{f}|H|B^0\rangle|^2-|\langle f|H|\bar{B}^0\rangle|^2)]\\ &-2\sin\Delta mt[\mathrm{Im}(e^{2i\phi_M}\langle f|H|B^0\rangle^*\langle f|H|\bar{B}^0\rangle)\\ &+\mathrm{Im}(e^{2i\phi_M}\langle \bar{f}|H|B^0\rangle^*\langle \bar{f}|H|\bar{B}^0\rangle)]\},\end{aligned} \tag{1}$$

$$\begin{aligned}\{\Gamma[B^0(t)\to f]+\Gamma[\bar{B}^0(t)\to \bar{f}]\}-\{\Gamma[B^0(t)\to \bar{f}]+\Gamma[\bar{B}^0(t)\to f]\} = e^{-\Gamma t}\{&\cos\Delta mt[(|\langle f|H|B^0\rangle|^2+|\langle \bar{f}|H|\bar{B}^0\rangle|^2)\\ &-(|\langle \bar{f}|H|B^0\rangle|^2+|\langle f|H|\bar{B}^0\rangle|^2)]\\ &-2\sin\Delta mt[\mathrm{Im}(e^{2i\phi_M}\langle f|H|B^0\rangle^*\langle f|H|\bar{B}^0\rangle)\\ &-\mathrm{Im}(e^{2i\phi_M}\langle \bar{f}|H|B^0\rangle^*\langle \bar{f}|H|\bar{B}^0\rangle)]\}.\end{aligned} \tag{2}$$

In Ref. [4], it was suggested that time-dependent $B \to D\pi$ decays can be used to find $\sin(2\beta+\gamma)$. The detailed analysis has been done in Refs. [5–7].

For $B \to D\pi$ decays, the decay amplitudes can be written as

$$\begin{aligned}A_{+-} &= \langle \bar{f}|H|\bar{B}^0\rangle = \langle D^+\pi^-|H|\bar{B}^0\rangle = \bar{A}_{\bar{f}},\\ A_{-+} &= \langle f|H|B^0\rangle = \langle D^-\pi^+|H|B^0\rangle = A_f, \quad A_f = \bar{A}_{\bar{f}},\\ A'_{-+} &= \langle f|H|\bar{B}^0\rangle = \langle D^-\pi^+|H|\bar{B}^0\rangle = e^{i\gamma}\bar{A}'_f,\\ A'_{+-} &= \langle \bar{f}|H|B^0\rangle = \langle D^+\pi^-|H|B^0\rangle = e^{-i\gamma}\bar{A}'_f.\end{aligned} \tag{3}$$

Note that the effective Lagrangians for decays $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^-\pi^+$ are given by

$$V_{cb}V^*_{ud}[\bar{d}\gamma^\mu(1+\gamma_5)u][\bar{c}\gamma_\mu(1+\gamma_5)b], \tag{4a}$$

$$V_{ub}V^*_{cd}[\bar{d}\gamma^\mu(1+\gamma_5)c][\bar{u}\gamma_\mu(1+\gamma_5)b], \tag{4b}$$

respectively. In the Wolfenstein parametrization of Cabibbo-Kobayashi-Maskawa quark-mixing (CKM) matrix

$$\frac{V_{cb}V^*_{ud}}{V_{ub}V^*_{cd}} = \lambda^2\sqrt{\rho^2+\eta^2}e^{i\gamma}. \tag{5}$$

Thus for $B \to D\pi$ decays, we get from Eqs. (1)–(3)

$$\begin{aligned}\mathcal{A}(t) &\equiv \frac{\{\Gamma[B^0(t)\to f]-\Gamma[\bar{B}^0(t)\to \bar{f}]\}}{\{\Gamma[B^0(t)\to f]+\Gamma[\bar{B}^0(t)\to \bar{f}]\}} = -\sin\Delta mt\sin(2\beta+\gamma)\frac{A^*_f\bar{A}'_f+A_f\bar{A}'^*_f}{|A_f|^2+|\bar{A}'_f|^2}\\ &= -\frac{2r}{1+r^2}\sin\Delta mt\cos(\delta_f-\delta'_f)\sin(2\beta+\gamma),\end{aligned} \tag{6}$$

$$\begin{aligned}\mathcal{F}(t) &\equiv \frac{\{\Gamma[B^0(t)\to f]+\Gamma[\bar{B}^0(t)\to \bar{f}]\}-\{\Gamma[B^0(t)\to \bar{f}]+\Gamma[\bar{B}^0(t)\to f]\}}{\{\Gamma[B^0(t)\to f]+\Gamma[\bar{B}^0(t)\to \bar{f}]\}+\{\Gamma[B^0(t)\to \bar{f}]+\Gamma[\bar{B}^0(t)\to f]\}}\\ &= \frac{|A_f|^2-|\bar{A}'_f|^2}{|A_f|^2+|\bar{A}'_f|^2}\cos\Delta mt + i\frac{A^*_f\bar{A}'_f-A_f\bar{A}'^*_f}{|A_f|^2+|\bar{A}'_f|^2}\sin\Delta mt\cos(2\beta+\gamma)\\ &= \frac{1-r^2}{1+r^2}\cos\Delta mt - \frac{2r}{1+r^2}\sin\Delta mt\cos(2\beta+\gamma)\sin(\delta_f-\delta'_f),\end{aligned} \tag{7}$$

 

where $r^2 = |\bar{A}'_f|^2/|A_f|^2$ and $f$ and $\bar{f}$ stand for $D^-\pi^+$ and $D^+\pi^-$ respectively. It is clear from Eqs. (6) and (7) that extraction of angle $2\beta + \gamma$ depends on the strong phases of amplitude $A_f$ and $\bar{A}'_f$ and parameter $r$.

The rest of the paper is concerned with the strong phases. First we consider the decays

$$\begin{aligned} \bar{B}^0(t) &\to D^+\pi^- \\ &\to D^0\pi^0 \\ B^-(t) &\to D^0\pi^-. \end{aligned}$$

The effective Lagrangian (4a) for these decays has $\Delta I = 1$. As is well known for these decays, isospin analysis gives

$$A_{+-} = \tfrac{1}{3}[A_{3/2} + 2A_{1/2}] = \tfrac{1}{3}[f_{3/2}e^{i\delta_{3/2}} + 2f_{1/2}e^{i\delta_{1/2}}]{:}T + A_2, \tag{8a}$$

$$A_{00} = -\frac{\sqrt{2}}{3}[A_{3/2} - A_{1/2}] = -\frac{\sqrt{2}}{3}[f_{3/2}e^{i\delta_{3/2}} - f_{1/2}e^{i\delta_{1/2}}]{:} -\frac{1}{\sqrt{2}}(C - A_2), \tag{8b}$$

$$A_{0-} = A_{3/2} = f_{3/2}e^{i\delta_{3/2}}{:}T + C, \tag{8c}$$

$$A_{+-} - \sqrt{2}A_{00} = A_{0-}, \tag{8d}$$

where $T$, $C$, $A_2$ denote contributions from the tree, the color suppressed, and $W$-exchange diagrams, respectively.

On the other hand for the effective Lagrangian (4b), we have both $\Delta I = 1$ and $\Delta I = 0$ parts. Thus for the decays

$$\begin{aligned} \overline{B}^0(t) &\to D^-\pi^+ \\ &\to \overline{D}^0\pi^0 \\ B^-(t) &\to D^-\pi^0 \\ &\to \overline{D}^0\pi^- \end{aligned}$$

the isospin analysis gives

$$A'_{-+} = -\frac{\sqrt{2}}{3}A'_{3/2} + \frac{\sqrt{2}}{3}C'_{1/2} - \sqrt{\frac{2}{3}}D'_{1/2}{:}T' + A'_2, \tag{9a}$$

$$A'_{00} = \frac{2}{3}A'_{3/2} + \frac{1}{3}C'_{1/2} - \frac{1}{\sqrt{3}}D'_{1/2}{:} -\frac{1}{\sqrt{2}}(C' - A'_2), \tag{9b}$$

$$A'_{-0} = -\frac{2}{3}A'_{3/2} - \frac{1}{3}C'_{1/2} - \frac{1}{\sqrt{3}}D'_{1/2}{:}\frac{1}{\sqrt{2}}(T' - A'_1), \tag{9c}$$

$$A'_{0-} = -\frac{\sqrt{2}}{3}A'_{3/2} + \frac{\sqrt{2}}{3}C'_{1/2} + \sqrt{\frac{2}{3}}D'_{1/2}{:}C' + A'_1, \tag{9d}$$

where $D'_{1/2}$ is the contribution from $\Delta I = 0$ part of the effective Lagrangian. Here it is convenient to write

$$C'_{1/2} - \sqrt{3}D'_{1/2} = A'_{1/2}, \qquad C'_{1/2} + \sqrt{3}D'_{1/2} = B'_{1/2}. \tag{10}$$

Thus we can write

$$A'_{-+} = -\frac{\sqrt{2}}{3}[A'_{3/2} - A'_{1/2}] = -\frac{\sqrt{2}}{3}[f'_{3/2}e^{i\delta'_{3/2}} - f'_{1/2}e^{i\delta'_{1/2}}], \tag{11a}$$

$$A'_{00} = \tfrac{1}{3}[2A'_{3/2} + A'_{1/2}] = \tfrac{1}{3}[2f'_{3/2}e^{i\delta'_{3/2}} + f'_{1/2}e^{i\delta'_{1/2}}], \tag{11b}$$

$$A'_{-0} = -\tfrac{1}{3}[2A'_{3/2} + B'_{1/2}] = -\tfrac{1}{3}[2f'_{3/2}e^{i\delta'_{3/2}} + g'_{1/2}e^{i\delta''_{1/2}}], \tag{11c}$$

$$A'_{0-} = -\frac{\sqrt{2}}{3}[A'_{3/2} - B'_{1/2}] = -\frac{\sqrt{2}}{3}[f'_{3/2}e^{i\delta'_{3/2}} - g'_{1/2}e^{i\delta''_{1/2}w}] \tag{11d}$$

$$A'_{-+} - \sqrt{2}A'_{00} = \sqrt{2}A'_{-0} + A'_{0-} \tag{11e}$$

In order to calculate the final state phases $\delta$'s, the following physical picture is useful. In the weak decays of $B$-mesons, the $b$-quark is converted into $b \to cq\bar{q}$, $b \to uq\bar{q}$; since for the [2,8–10] tree graph the configuration is such that $q$ and $\bar{q}$ essentially go togather into a color singlet state with the third quark recoiling, there is a significant probability that the system will hadronize as a two body final state. Thus the strong phase shifts are expected to be small at least for tree amplitude. They are generated after hydronization by rescattering.

As noted in Ref. [11], in the simple factorization ansatz (large $N_c$ limit), $C$ and $A_2$ vanish so that the decay $\bar{B}^0 \to D^0\pi^0$ entirely arises from rescattering:

$$\bar{B}^0 \to D^+\pi^- \to D^0\pi^0.$$

Thus, the rescattering involves charge exchange; hence it is determined by an isospin one exchange trajectory. The isospin decomposition of the scattering amplitude $\pi_i D \to \pi_j D$ can be expressed in terms of two amplitudes

$$M_{ji} = M^{(+)}\delta_{ji} + \tfrac{1}{2}M^{(-)}[\tau_j, \tau_i]. \tag{12}$$

The $I = 3/2$ and $I = 1/2$ scattering amplitudes are related to $M^{(+)}$ and $M^{(-)}$ as follows

$$M_{3/2} = M^{(+)} - M^{(-)} M_{1/2} = M^{(+)} + 2M^{(-)}.$$

Since an isospin one exchange contributes to $M^{(-)}$, we get [11]

$$\frac{M_{3/2}}{M_{1/2}} = -\frac{1}{2}. \tag{13}$$

In order to consider the rescattering corrections to the decays $\bar{B}^0 \to D^0\pi^0$ and $\bar{B}^0 \to \bar{D}^0\pi^0$, we note that the unitarity gives the imaginary part of the decay amplitude $A_f$ as follows:

$$\mathrm{Im}A_f = \sum_n M^*_{nf}A_n, \tag{14}$$

where $M_{nf}$ is the scattering amplitude for $f \rightarrow n$ and $A_n$ is the decay amplitude $\bar{B}^0 \rightarrow n$. In dispersion relation two particle unitarity gives dominant contribution. The dominant contribution is expected to be from the intermediate state $n = f'$ ($f' = \pi^- D^+$ or $\pi^+ D^-$). Other possible two particle states which may contribute are $\pi^- D^{*+}(\pi^+ D^{*-})$ or $\rho^- D^+(\rho^+ D^-)$. But it is important to note that $\bar{B}^0 \rightarrow \pi^- D^+(\pi^+ D^-)$ decays are $s$-wave decays whereas $\pi^- D^{*+}(\pi^+ D^{*-})$ are $p$-wave decays. Hence the scattering amplitude connecting $p$-wave intermediate states with $s$-wave final states in Eq. (14) will not contribute. Similar remarks hold for $\rho^- D^+(\rho^+ D^-)$ states.

Now the scattering amplitude $M_{ff'}$ is given by $I = 1$ ($\rho$ trajectory) exchange in the $t$-channel. Then using unsubtracted dispersion for the decay amplitude $A_f$, the rescattering correction to $A_f$ can be written in the form $\epsilon e^{i\theta} A_{f'}$ [12–14].

Hence taking into account the rescattering correction, Eqs. (8b) and (11b) are modified to

$$A_{00} = -\frac{1}{\sqrt{2}}(C - A_2) - \sqrt{2}\epsilon e^{i\theta} T, \tag{15}$$

$$A'_{00} = -\frac{1}{\sqrt{2}}(C' - A'_2) - \sqrt{2}\epsilon e^{i\theta} T'. \tag{16}$$

Note an important fact that $I = 1$ exchange in the $t$-channel gives the same contribution to rescattering amplitudes both for $\pi D$ and $\pi\bar{D}$ channels. This is a consequence of $C$-invariance of scattering amplitude:

$$\begin{aligned} M_{ff'} &= \langle \pi^0 D^0 | M | \pi^- D^+ \rangle \\ &= \langle \pi^0 D^0 | C^{-1} C M C^{-1} C | \pi^- D^+ \rangle \\ &= \langle \pi^0 \bar{D}^0 | M | \pi^+ D^- \rangle. \end{aligned} \tag{17}$$

First we note that the strong phases are generated after hadronization, i.e., they are negligibly small in the absence of rescattering. Hence in the absence of rescattering

$$\begin{aligned} A_{00} &= -\frac{\sqrt{2}}{3}[f_{3/2} - f_{1/2}] = -\frac{1}{\sqrt{2}}(C - A_2) \\ &= -\frac{1}{\sqrt{2}}(2b)T, \end{aligned} \tag{18}$$

where

$$2b = \frac{C - A_2}{T}. \tag{19}$$

Now in high $N_c$ limit $(C - A_2) \rightarrow 0$, $f_{3/2} = f_{1/2}$. But for finite but small $b$, we get from Eq. (18)

$$\frac{f_{1/2}}{f_{3/2}} = \frac{(1 - b)}{1 + 2b}. \tag{20}$$

Similarly, we get

$$-\frac{f'_{1/2}}{2f'_{3/2}} = \frac{(1 - b)}{1 + 2b}. \tag{21}$$

Secondly, after rescattering correction, $A_{00}$ is given by [cf. Eq. (15)]

$$A_{00} = -\frac{\sqrt{2}}{3}[(f_{3/2} - f_{1/2}) - \epsilon e^{i\theta}(f_{3/2} + 2f_{1/2})]. \tag{22}$$

We note that in the presence of rescattering $A_{00}$ is modified and can be written in the form

$$A_{00} = -\frac{\sqrt{2}}{3}[\tilde{f}_{3/2} e^{i\delta_{3/2}} - \tilde{f}_{1/2} e^{i\delta_{1/2}}]. \tag{23}$$

Comparison with Eq. (22) gives

$$\tilde{f}_{3/2} = f_{3/2}(1 + \epsilon\cos\theta), \quad \tilde{f}_{1/2} = f_{1/2}(1 - 2\epsilon\cos\theta), \tag{24}$$

$$\tilde{f}_{3/2}\delta_{3/2} - \tilde{f}_{1/2}\delta_{1/2} = \epsilon\sin\theta(f_{3/2} + 2f_{1/2}). \tag{25}$$

Neglecting the terms of order $\epsilon\delta$, we get from Eq. (25)

$$f_{3/2}\delta_{3/2} - f_{1/2}\delta_{1/2} = \epsilon\sin\theta(f_{3/2} + 2f_{1/2}). \tag{26}$$

From Eq. (26), using Eq. (20), we get

$$(\delta_{3/2} - \delta_{1/2}) + b(2\delta_{3/2} + \delta_{1/2}) = 3\epsilon\sin\theta. \tag{27}$$

Since right hand side of Eq. (27) is independent of $b$, we obtain

$$\delta_{1/2} = -2\delta_{3/2}, \delta_{3/2} = \epsilon\sin\theta. \tag{28}$$

Similarly we get

$$2f'_{3/2}\delta'_{3/2} + f'_{1/2}\delta'_{1/2} = 2\epsilon\sin\theta(f'_{3/2} - f'_{1/2}). \tag{29}$$

Then using Eq. (21), we get

$$\delta'_{1/2} = -2\delta'_{3/2}, \delta'_{3/2} = \epsilon\sin\theta. \tag{30}$$

Equations (28) and (30) are our main results. From these results, it follows that $\delta'_f = \delta_f$ [see below].

Hence, we get from Eq. (6) and (7),

$$\mathcal{A}(t) = -\frac{2r}{1 + r^2}\sin\Delta mt\sin(2\beta + \gamma), \tag{31}$$

$$\mathcal{F}(t) = \frac{1 - r^2}{1 + r^2}\cos\Delta mt. \tag{32}$$

It is clear from Eqs. (31) and (32) that $CP$-asymmetry is independent of final state phase $\delta = \delta_f - \delta'_f$. Thus both the phase $2\beta + \gamma$ and the ratio $r$ can be determined from the experimental values of $\mathcal{A}(t)$ and $\mathcal{F}(t)$. This result is also relevant for the recent measurement of time-dependent $CP$ asymmetries for the $B^0 \rightarrow D^{*\mp}\pi^{\pm}$ decays by BaBar Collaboration [15]. With $\delta = 0$, their measurement of $CP$-asymmetries contain only one parameter $r$, instead of two for determining $\sin(2\beta + \gamma)$.

Now from Eq. (8), using Eqs. (20) and (28), we obtain

$$A_f \equiv A_{+-} = f_{3/2}\frac{1}{1+2b}e^{-i\delta_f} \equiv |A_f|e^{-i\delta_f},$$
$$A_{00} = -\sqrt{2}\times f_{3/2}\frac{1}{1+2b}(a+i\delta_{3/2}), \qquad (33)$$
$$A_{0-} = f_{3/2}e^{i\delta_{3/2}},$$

where

$$\delta_f = (1-2b)\delta_{3/2}, \qquad (34)$$

$$a = b + \epsilon\cos\theta. \qquad (35)$$

Similarly, from Eq. (11a), using Eqs. (21) and (30), we get

$$\bar{A}'_f \equiv A'_{-+} = -\frac{\sqrt{2}}{1+2b}f'_{3/2}e^{-i\delta'_f} \equiv |\bar{A}'_f|e^{-i\delta'_f}, \qquad (36)$$

where

$$\delta'_f = (1-2b)\delta'_{3/2} = \delta_f. \qquad (37)$$

Finally, we get from Eqs. (33),

$$R_{+-} \equiv \frac{\Gamma(\bar{B}^0 \to D^+\pi^-)}{\Gamma(B^- \to D^0\pi^-)} = \frac{1}{(1+2b)^2} \approx 0.57 \pm 0.09, \qquad (38)$$

$$R_{00} \equiv \frac{\Gamma(\bar{B}^0 \to D^0\pi^0)}{\Gamma(B^- \to D^0\pi^-)} = \frac{2}{(1+2b)^2}(a^2+\delta_{3/2}^2) \approx 0.06 \pm 0.01, \qquad (39)$$

where the numbers on the right hand side of Eqs. (38) and (39) are experimental values [16].

From the above equations, we obtain

$$b \approx 0.162, \qquad a^2 + \delta_{3/2}^2 = 0.053. \qquad (40)$$

Further we note that

$$\delta_{3/2} = \epsilon\sin\theta \leq \epsilon. \qquad (41)$$

Thus we cannot get the magnitude of phase shift unless we know $\theta$. But it is expected to be small, since $\epsilon \sim 1/m_B$. In particular for

$$\theta = 90^0, \delta_{3/2} = \epsilon, \quad a = b, \qquad (42)$$

$$\delta_{3/2} \approx 0.162 \approx 9^0. \qquad (43)$$

To conclude based on the assumption that final state phase shifts are small; they are generated by rescattering, we have obtained $\delta'_{3/2} = \delta_{3/2}$, $\delta'_{1/2} = \delta_{1/2} = -2\delta_{3/2}$, $\delta'_f = \delta_f$. The equality of phase shifts for $\pi D$ and $\pi\bar{D}$ channels (which are $C$-conjugate of each other) is essentially a consequence of $C$-invariance of scattering amplitude $M_{nf}$ for these channels.

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