

Final state phases in $B \rightarrow D\pi$, $\bar{D}\pi$ decays and CP asymmetry

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Final state phases δ_f and δ'_f in $B \rightarrow D\pi$, $\bar{D}\pi$ 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 δ_f and δ'_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 γ 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])

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

$$\begin{aligned} \{\Gamma[B^0(t) \rightarrow f] + \Gamma[\bar{B}^0(t) \rightarrow \bar{f}]\} - \{\Gamma[B^0(t) \rightarrow \bar{f}] + \Gamma[\bar{B}^0(t) \rightarrow f]\} = e^{-\Gamma t} \{ \cos \Delta m t [(|\langle f|H|B^0\rangle|^2 + |\langle \bar{f}|H|\bar{B}^0\rangle|^2) \\ - (|\langle \bar{f}|H|B^0\rangle|^2 + |\langle f|H|\bar{B}^0\rangle|^2)] \\ - 2 \sin \Delta m t [\text{Im}(e^{2i\phi_M} \langle f|H|B^0\rangle^* \langle f|H|\bar{B}^0\rangle) \\ - \text{Im}(e^{2i\phi_M} \langle \bar{f}|H|B^0\rangle^* \langle \bar{f}|H|\bar{B}^0\rangle)] \}. \end{aligned} \quad (2)$$

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

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

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

Note that the effective Lagrangians for decays $\bar{B}^0 \rightarrow$

$D^+ \pi^-$ and $\bar{B}^0 \rightarrow D^- \pi^+$ are given by

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

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

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

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

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

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

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

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

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

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

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

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

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

$$A_{+-} - \sqrt{2}A_{00} = A_{0-}, \quad (8d)$$

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

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

the isospin analysis gives

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

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

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

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

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

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

Thus we can write

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

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

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

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

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

In order to calculate the final state phases δ 's, the following physical picture is useful. In the weak decays of B -mesons, the b -quark is converted into $b \rightarrow c q \bar{q}$, $b \rightarrow u q \bar{q}$; since for the [2,8-10] tree graph the configuration is such that q and $\bar{q}$ essentially go together 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 hadronization 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 $\bar{B}^0 \rightarrow D^0 \pi^0$ entirely arises from rescattering:

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

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

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

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]

$$\frac{M_{3/2}}{M_{1/2}} = -\frac{1}{2}. \quad (13)$$

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

$$\text{Im}A_f = \sum_n M_{nf}^* A_n, \quad (14)$$

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 $I = 1$ (ρ 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

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

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

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

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

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

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

where

$$2b = \frac{C - A_2}{T}. \quad (19)$$

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)

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

Similarly, we get

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

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

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

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

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

Comparison with Eq. (22) gives

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

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

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

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

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

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

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

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

Similarly we get

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

Then using Eq. (21), we get

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

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),

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

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

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

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

where

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

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

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

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

where

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

Finally, we get from Eqs. (33),

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

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

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

From the above equations, we obtain

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

Further we note that

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

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

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

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

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 πD 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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