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Enhanced CP Violation with $B \to KD^0(\overline{D}^0)$ Modes and Extraction of the CKM Angle γ

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Abstract

The Gronau-London-Wyler (GLW) method extracts the CKM angle γ by measuring $B^\pm$ decay rates involving $D^0/\overline{D}^0$ mesons. Since that method necessitates the interference between two amplitudes that are significantly different in magnitude, the resulting asymmetries tend to be small. CP violation can be greatly enhanced for decays to final states that are common to both D^0 and $\overline{D}^0$ and that are not CP eigenstates. In particular, large asymmetries are possible for final states f such that $D^0 \to f$ is doubly Cabibbo suppressed while $\overline{D}^0 \to f$ is Cabibbo allowed. The measurement of interference effects in two such modes allows the extraction of γ without prior knowledge of $Br(B^- \to K^-\overline{D}^0)$, which may be difficult to determine due to backgrounds.

One striking implication of the standard model with three families is that it can accommodate CP violation via the Kobayashi-Maskawa mechanism [1]. Intense experimental efforts are now underway in B-physics to test the standard model in this regard through measurements of the unitarity triangle [2]. For this program to succeed it is of crucial importance to be able to deduce each of the angles of this triangle from experiment. In this paper we will focus our attention to one of the three angles, namely γ.

We recall that in the standard model, $b \to c\overline{u}s$ and $b \to \overline{c}us$ transitions have a relative Cabibbo-Kobayashi-Maskawa (CKM) phase γ. In order to measure CP violation due to this phase, a means must be found to have these seemingly distinct final states interfere. A mechanism whereby this is possible has been proposed and extensively studied [3,4,5,6,7,8].

The basic idea is that if the $\overline{u}c$ ($\overline{c}u$) hadronize into a single D^0 ($\overline{D}^0$) meson, which is subsequently seen as a CP eigenstate (e.g. $K_S\pi^0$) or $K_S + n\pi$, then both processes lead to a common final state. These two channels can thus interfere quantum mechanically giving rise to, in particular, CP violating effects [3].

The Gronau-London-Wyler (GLW) method [4,5,6,7,8] extracts the CKM angle γ from measurements of the branching ratios of the six processes, $B^- \to K^-\overline{D}^0$, K^-D^0, $K^-D^0_{CP}$ and their CP-conjugate partners. Here D^0_{CP} denotes that the D^0 or the $\overline{D}^0$ is seen in a CP eigenstate. The two interfering amplitudes have a CP violating phase γ between the D^0 and the $\overline{D}^0$ paths leading to the common final state. The manifestation of CP violation also requires a CP even phase difference. This will generally be present due to final state interactions although it is not known how to calculate it reliably. However, even if this strong phase difference is small, information about γ may still be extracted from CP even interference effects.

The use of D^0 and $\overline{D}^0$ decays to common states that are *not CP eigenstates* was proposed several years ago [7]. In this Letter we wish to point out that among this category, D^0 decays which are doubly Cabibbo suppressed lead to CP violating effects that may be greatly enhanced. In addition, a number of potential experimental difficulties with the GLW method may be reduced or overcome.

The primary problem with respect to the GLW method is the fact that CP violating asymmetries tend to be small since $B^- \to K^-\overline{D}^0$ is color suppressed whereas $B^- \to K^-D^0$ is color allowed. Moreover, when the appropriate CKM factors are taken into account, the former amplitude is typically an order of magnitude smaller than the latter. In the GLW method the interference effects are therefore limited to $O(10\%)$, which indicates the maximum possible size for CP violation via this method. To overcome this we choose instead D^0-modes, f, that are not CP-eigenstates. Especially appealing are modes f such that $D^0 \to f$ is doubly Cabibbo suppressed while $\overline{D}^0 \to f$ is Cabibbo allowed (e.g. $f = K^+\pi^-$, $K\pi\pi$, etc.). As a result, the two interfering amplitudes become comparable. Numerically, the ratio between these two amplitudes is crudely given by [9]:

$$\left|\frac{\mathcal{M}(B^- \to K^- D^0[\to f])}{\mathcal{M}(B^- \to K^- \overline{D}^0[\to f])}\right|^2 \approx \left|\frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 \quad \left|\frac{a_1}{a_2}\right|^2 \quad \frac{Br(D^0 \to f)}{Br(\overline{D}^0 \to f)} \approx \tag{1}$$
$$\approx \left|\frac{0.22}{0.08}\right|^2 \quad \left|\frac{1}{0.26}\right|^2 \quad 0.0077 \sim 1 \ ,$$

where $\mathcal{M}$ denotes the amplitude for the given process. Here the color-suppressed amplitude ($\sim a_2$) is reduced with respect to the color-allowed one ($\sim a_1$) by the factor suggested in [10]:

$$|a_2/a_1| \approx 0.26,$$

and the ratio of CKM elements $|V_{ub}/V_{cb}| \approx 0.08$ was used.

While a naive estimate for the ratio of twice Cabibbo suppressed to Cabibbo-allowed branching ratio is

$$\frac{Br(D^0 \to f)}{Br(\overline{D}^0 \to f)} \approx \left|\frac{V_{cd}V_{us}}{V_{cs}V_{ud}}\right|^2 \approx \lambda^4 \ , \tag{2}$$

form-factor and decay constant ratios may increase it somewhat. Such a ratio has been observed by CLEO [11]

$$\frac{Br(D^0 \to K^+\pi^-)}{Br(\overline{D}^0 \to K^+\pi^-)} = 0.0077 \pm 0.0025 \pm 0.0025 \ ,$$

whose central value was used in Eq. (1) for the generic ratio.

The balancing of the amplitudes illustrated in Eq. (1) suggests that CP violating effects in the interference of two amplitudes of this type can be large. Let us define, for a general final state f, the CP violating partial rate asymmetry:

$$A(K,f) \equiv \frac{Br(B^- \to K^-[f]) - Br(B^+ \to K^+[\overline{f}])}{Br(B^- \to K^-[f]) + Br(B^+ \to K^+[\overline{f}])}$$

where the square bracket denotes that the bracketed mode originates from a $D^0/\overline{D}^0$ decay. Based on the above argument potentially the largest CP violating asymmetry $A(K,f)$ in $B^\pm$ decays involving $D^0 - \overline{D}^0$ interference occurs when f is a doubly Cabibbo suppressed decay mode of the D^0.

In the GLW method where f is a CP eigenstate, the strong phase difference between $D^0 \to f$ and $\overline{D}^0 \to f$:

$$\delta_f = \arg(\mathcal{M}(D^0 \to f)\mathcal{M}(\overline{D}^0 \to f)^*)$$

is to an excellent approximation 0 mod π [12]. Therefore the total strong phase difference involved is that of the initial B decay, ζ_K mod π, where ζ_K is given by:

$$\zeta_K = \frac{1}{2}\arg\left[\mathcal{M}(B^- \to K^- D^0)\mathcal{M}(B^- \to K^-\overline{D}^0)^*\mathcal{M}(B^+ \to K^+ D^0)^*\mathcal{M}(B^+ \to K^+\overline{D}^0)\right] .$$

Since $A(K, f) \propto \sin(\zeta_K + \delta_f) = \pm\sin(\zeta_K)$, if ζ_K should happen to be small the GLW method will produce only a small CP violating signal. In contrast, for non-CP eigenstates f, δ_f may assume different values, some of which could be large. Indeed some experimental evidence suggests that final state interaction effects in such D^0 decays can be appreciable [13]. Since several such modes are experimentally feasible, for instance $f = K^+\pi^-$, $K^+\rho^-$, $K^+a_1^-$, $K^{*+}\pi^-$, $K\pi\pi$, etc., it is likely that for at least some of these $\sin(\zeta_K + \delta_f)$ will be large leading to a large asymmetry $A(K, f)$.

Another potential problem that arises with the GLW method is that to reconstruct γ it is necessary to know separately the branching ratios $Br(B^- \to K^- D^0)$ and $Br(B^- \to K^-\overline{D}^0)$. While $Br(B^- \to K^- D^0) \sim O(10^{-4})$ can be measured via conventional methods, $Br(B^- \to K^-\overline{D}^0) \sim O(10^{-6})$ suffers from some serious experimental difficulties.

First, if $Br(B^- \to K^-\overline{D}^0)$ is measured through the use of hadronic decays of the $\overline{D}^0$ (e.g. $\overline{D}^0 \to K^+\pi^-$) then, as Eq. (1) demonstrates, interference effects of $O(1)$ with the D^0 channel (e.g. $B^- \to K^- D^0[\to K^+\pi^-]$) will be present. Clearly then, the $\overline{D}^0$ must be tagged with a decay that is distinct from any decay of the D^0, for instance the semileptonic decay $\overline{D}^0 \to l^-\overline{\nu}_l X_{\overline{s}}$. This mode, however is subject to daunting backgrounds, such as $B^- \to l^-\overline{\nu}_l X_c$ which is $O(10^6)$ times larger. Such backgrounds may be difficult to overcome [14].

In our technique, the possibility of having a variety of strong phases allows for several methods for the extraction of γ [15]. For brevity, we will mention only two in this Letter. We assume here all relevant branching ratios for D^0 decays are known.

In method (1) we assume that $Br(B^- \to K^- D^0)$ is known but not $Br(B^- \to K^- \overline{D}^0)$. We also require the experimental determination of BR's for at least two distinct final states f_1 and f_2 (where at least one of f_1, f_2 is not a CP eigenstate):

$$Br\left(B^- \to K^- \left[f_i\right]\right) \ , \quad Br\left(B^+ \to K^+ \left[\overline{f}_i\right]\right) \ , \quad \text{for} \quad i = 1, 2 \ .$$

This information suffices to extract γ, $Br(B^- \to K^- \overline{D}^0)$, and the two relevant strong phase differences up to some discrete ambiguity.

To see how this works, let us define the quantities:

$$a(K) = Br(B^- \to K^- D^0) \quad b(K) = Br(B^- \to K^- \overline{D}^0) \quad c(f_i) = Br(D^0 \to f_i)$$
$$c(\overline{f}_i) = Br(D^0 \to \overline{f}_i) \quad d(K, f_i) = Br(B^- \to K^-[f_i]) \quad \overline{d}(K, f_i) = Br(B^+ \to K^+[\overline{f}_i])$$

where $i = 1, 2$. In this case, therefore, we know the quantities $a(K)$, $c(f_i)$, $c(\overline{f}_i)$, $d(K, f_i)$, $\overline{d}(K, f_i)$ but not $b(K)$.

The expressions for $d(K, f_i)$, $\overline{d}(K, f_i)$ in terms of the strong phases and γ gives us four equations:

$$\begin{aligned} d(K, f_i) &= a(K)c(f_i) + b(K)c(\overline{f}_i) + 2\sqrt{a(K)b(K)c(f_i)c(\overline{f}_i)}\cos(\xi^K_{f_i} + \gamma) \\ \overline{d}(K, f_i) &= a(K)c(f_i) + b(K)c(\overline{f}_i) + 2\sqrt{a(K)b(K)c(f_i)c(\overline{f}_i)}\cos(\xi^K_{f_i} - \gamma) \end{aligned} \tag{3}$$

where $\xi^K_{f_i} = \zeta_K + \delta_{f_i}$. These four equations contain the four unknowns $\{\xi^K_{f_1},\ \xi^K_{f_2},\ b(K),\ \gamma\}$ which therefore can be determined up to discrete ambiguities. Adding additional modes will, in general, reduce the ambiguity to an overall two-fold one in the sign of all the phases.

This method also illustrates the importance of D decay studies in interpreting such CP violation in B decays. The strong phases $\xi^K_{f_i}$ relevant to eq. (3) are related to the D decay phase shifts δ_{f_i} via

$$\xi^K_{f_1} - \xi^K_{f_2} = \delta_{f_1} - \delta_{f_2} \tag{4}$$

Since the separate phase shifts δ_{f_i} on the right hand side of (4) may be determined from data at a ψ'' charm factory [15,16] or from detailed studies of D decays [17], this relation puts an additional constraint on the system of equations (3). Indeed, if δ_{f_1} and δ_{f_2} are known then ζ_K may also be extracted, thereby providing information about final state interaction effects in B decays. Conversely, if the left hand side of eq. (4) is determined from studies of CP violation, information is obtained about D decay phase shifts.

Method (2) is a straightforward generalization of the GLW method. Instead of a CP-eigenstate, a non-CP eigenstate f is used. In addition to $Br(B^- \to K^- D^0)$, we assume that $Br(B^- \to K^- \overline{D}^0)$ is accurately known as well as the following branching ratios:

$$Br(B^- \to K^-[f]) \ , \ \ Br(B^+ \to K^+[\overline{f}]) \ .$$

Thus, for the mode f we know $a(K)$, $b(K)$, $c(f)$, $c(\overline{f})$, $d(K, f)$ and $\overline{d}(K, f)$. We see that eq. (3) (for $f_i = f$) is now a system of two equations in two unknowns $\{\gamma,\ \xi_f^K\}$ and can therefore be solved. This system of equations is identical to the geometric construction in [4,5,6]. Using additional distinct modes f' will reduce ambiguities and determine γ more accurately. There are several variations and straightforward generalizations of these methods of extracting γ, which will be discussed in detail elsewhere [15].

The discussion above as it applies to $B^- \to K^- D^0$ versus $K^- \overline{D}^0$ in fact may be generalized with little modification to B decays of the form $B^- \to \mathbf{k}^- \mathbf{d}^0$ versus $\mathbf{k}^- \overline{\mathbf{d}}^0$ where $\mathbf{k}^-$ denotes K^-, K^{*-} or any higher kaonic resonance. Likewise $\mathbf{d}^0$ denotes D^0, D^{*0} or any higher D-resonance where that excited state cascades down to a D^0 that in turn decays to final states accessible to both D^0 and $\overline{D}^0$. This immediate generalization is constrained to cases where $\mathbf{k}^-$ or $\mathbf{d}$ is spin 0 or else several partial waves will be present. The case with multiple partial waves may still be considered except that each of the amplitudes may have a different strong phase and so must be separated. Of course if this analysis can be done, it may provide an advantage since method (1) could then be applied to several amplitudes with the same particles in the final state.

Let us now give a rough numerical estimate of the typical size of the asymmetry $A(K, f)$ and the number of $B's$ needed to observe the effect using our method. We shall perform the estimate for the case $B^- \to K^{*-}[K^+\rho^-]$. We start with the known branching ratio

$Br(B^- \to \rho^- D^0) = 1.3\%$. Multiplying this by the Cabibbo factor of $\sin^2\theta_C$ one obtains an estimate of $a(K^*) \approx 6.6 \times 10^{-4}$. Using the ratio in Eq. 1, one obtains $b(K^*) \approx 6 \times 10^{-6}$. The experimental value of $c(K^-\rho^+) = .11$. To estimate the value of $c(K^+\rho^-)$ let us suppose that $c(K^-\pi^+) : c(K^+\pi^-) = c(K^-\rho^+) : c(K^+\rho^-)$, thus $c(K^+\rho^-) \approx 8.5 \times 10^{-4}$.

In terms of the angles $\xi^{K^*}_{K^+\rho^-}$ and γ, the partial rate asymmetry A is given by:

$$A(K^*, K^+\rho^-) = -R(K^*, K^+\rho^-) \sin\xi^{K^*}_{K^+\rho^-} \sin\gamma / (1 + R(K^*, K^+\rho^-) \cos\xi^{K^*}_{K^+\rho^-} \cos\gamma) \quad (5)$$

where

$$R(K^*, K^+\rho^-) = \frac{2\sqrt{a(K^*)b(K^*)c(K^+\rho^-)c(K^-\rho^+)}}{a(K^*)c(K^+\rho^-) + b(K^*)c(K^-\rho^+)} \quad (6)$$

For the numbers above then $R = .99$. In order to estimate the asymmetry A however, we need to know the value of the weak and strong phases which are not very well constrained experimentally. For the purpose of our estimates, let us take $\cos\xi^{K^*}_{K^+\rho^-} \cos\gamma = 0$ so that the denominator in eq. (5) assumes its average value and also $\sin\xi^{K^*}_{K^+\rho^-} \sin\gamma = 1/2$ where $1/2$ is the r.m.s average value of $\sin\theta_1 \sin\theta_2$ for randomly selected $\{\theta_1, \theta_2\}$. The resulting asymmetry is, $A \sim 50\%$. Let us now define $N^{3\sigma}$ to be the total number of charged B's (i.e. $N^{3\sigma} = N(B^+) + N(B^-)$) required to observe the asymmetry A to a $3-\sigma$ significance. This quantity is thus given by:

$$N^{3\sigma} = \frac{18}{A^2[d(K^*, K^+\rho^-) + \overline{d}(K^*, K^+\rho^-)]} \quad (7)$$

which in this case would be $N^{3\sigma} \approx 5.9 \times 10^7$. Similarly for the case of $B^- \to K^{*-}[K^+\pi^-]$ $N^{3\sigma} \approx 15 \times 10^7$.

As a comparison, one can perform a similar estimate for the case where f is a CP eigenstate as in the GLW method. Thus if we take $f = K_S\pi^0$, and assume $\sin\zeta_K \sin\gamma = 1/2$; $\cos\zeta_K \cos\gamma = 0$, we get $R \approx .19$, $A \approx 9.5\%$, and finally $N^{3\sigma} \approx 31 \times 10^7$. In the GLW method it is possible to properly combine statistics for all CP eigenstate modes. If one does not include modes with K_L this amounts to a branching fraction which is roughly 5% of D^0 decays. Taking 5%, we find that $N^{3\sigma} \approx 6.5 \times 10^7$, about the same as for our single mode above. In [15] similar estimates are performed for the modes $B^- \to K^-[K^+\rho^-]$, $K^-[K^+\pi^-]$, $K^{*-}[K^+\pi^-]$, $K^-[K^+a_1^-]$, $K^{*-}[K^+a_1^-]$, $K^-[K^{*+}\pi^-]$ and $K^{*-}[K^{*+}\pi^-]$ each of which produces results for A and $N^{3\sigma}$ of the same order of magnitude as the $B^- \to K^{*-}[K^+\rho^-]$ case.

An important point to bear in mind about CP non-eigenstate modes such as $K^{*+}\pi^-$ and $K^+\rho^-$ is that they are just approximations to concentrations in the Dalitz plot for $K\pi\pi$. In full generality each point of this Dalitz plot contains a separate value of δ. In principle, one can generate a set of equations (3) at each such point and then proceed to extract γ as in method (1). In practice, if the variation of the strong phase is accurately known or well modelled, one can weight information optimally to extract γ. Such a Dalitz plot analysis, which may be generalized to n-body decays, is discussed extensively in [15]. Comparing such a generalized Dalitz plot of f for a B decay with its CP conjugate partner could show striking CP violating effects. The numerical estimates above do, however, provide a rough idea of the reach of such modes.

Finally, let us comment on D^0 decay modes which are singly Cabibbo suppressed yet not CP eigenstates such as $K^{*\pm}K^{\mp}$, $K^{**\pm}K^{(*)\mp}$, $\pi^{\pm}\rho^{\mp}$, $\pi^{\pm}a_1^{\mp}$, $\rho^{\pm}a_1^{\mp}$, etc. Since for these modes the quark content is self conjugate, $c(f) \approx c(\overline{f})$. Thus, as with the true CP eigenstate modes of the GLW method, the CP violating effects from $B^- \to K^-[f]$ will be $O(10\%)$ and $N^{3\sigma}$ will be similar to that estimated above for the GLW case. On the other hand, in B^0 decays both the modes $B^0 \to \mathbf{k}^0 D^0$ and $B^0 \to \mathbf{k}^0 \overline{D}^0$ are color suppressed and so $D^0(\overline{D}^0)$ decays to such singly Cabibbo suppressed modes could lead to large CP asymmetries. Indeed such an approach, which provides an additional strong phase difference due to D^0 decays may significantly enhance the methods discussed in [4,6] where CP eigenstates are used.

In summary, we reiterate the potential limitations of the GLW method:

(a) One must observe decays of D^0 to a CP eigenstate. All such modes are either Cabibbo suppressed or color suppressed and the experimentally feasible total (ignoring K_L modes) is less than 5%.

(b) The CP violating asymmetries from the decays of D^0 to CP eigenstates are

$O(10\%)$ at best, whereas more dramatic asymmetries would be desirable.

(c) The GLW method requires knowledge of the branching ratios $B(B^- \to K^- D^0)$ and $B(B^- \to K^- \overline{D}^0)$ where the latter may present experimental difficulties.

(d) If it should happen that the strong phase difference between $\mathcal{M}(B^- \to K^- D^0)$ and $\mathcal{M}(B^- \to K^- \overline{D}^0)$ is small, then no observable CP violation will be produced even though one may still be able to deduce $\cos\gamma$.

In our method, problem (a) is overcome since there are a large number of different modes that one can use. Using the decay chains $B^- \to K^- D^0[\to f]$ and $K^- \overline{D}^0[\to f]$ (where f is a doubly Cabibbo-suppressed mode of D^0, and thus Cabibbo favored mode of $\overline{D}^0$) the event rate is reduced but this plays to our benefit since asymmetries of $O(100\%)$ are likely in at least some modes [see problem (b)]. More detailed estimates [15] show that the required number of B events are favorable (at worst comparable) in comparison to the original GLW method for extracting the CKM angle γ. Problem (c) can be circumvented because we can dispense with the need to know $Br(B^- \to K^- \overline{D}^0)$ by considering different hadronic final states f_i of neutral D mesons with different strong phases. In such cases we can solve for $Br(B^- \to K^- \overline{D}^0)/Br(B^- \to K^- D^0)$ and γ. Problem (d) is unlikely in our case because for non-CP eigenstate modes f_i, the strong phase difference between the two interfering B decay amplitudes [$\mathcal{M}(B^- \to K^- D^0)$ and $\mathcal{M}(B^- \to K^- \overline{D}^0)$] is combined with an additional strong phase difference in D decays, δ_{f_i}. Judicious choices of D^0 modes thus allow potentially large strong phase differences, thereby significantly enhancing CP violating effects in B decays involving $D^0/\overline{D}^0$ mesons.

In closing, we recall that various B detectors currently under construction are specifically designed to observe mixing-induced CP violation. Such experiments should be able to determine the CKM phase β without any assumption concerning strong phases. Likewise both for the original GLW method [5] and our version, γ is reconstructed (up to discrete ambiguities) without any assumption about the value of the strong phase. The ability to probe γ more incisively, improves our capacity to constrain or rule out the standard model. In addition, since these methods measure direct CP violation rather than oscillation effects, one may perform such experiments at any facility where B mesons are copiously produced. Because neither tagging nor time-dependent studies are required, such effects could be observed at even a symmetric $\Upsilon(4S)$ factory, such as CLEO. To optimize the observation and interpretation of such effects, accurate measurements of the relevant D^0 decays are highly desirable.

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