Direct CP Violation in a Variety of B Decays

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We give a brief review of direct CP violation effects in charmless B decays, both at the inclusive and at the exclusive level. It is emphasized that typical exclusive final states are composed of 2–4 K or π 's, hence particle identification (in terms of K/π separation) is of crucial importance for studying CP violation in these modes. Another kind of “charmless” final state is also emphasized: $b \rightarrow d\bar{c}\bar{c}$. The decay rate is tree dominant, while “ q^2 ” is necessarily above $c\bar{c}$ threshold hence in the domain of perturbative QCD. The CP asymmetry is therefore relatively clean and reliable. Theoretically, a few $\times 10^7$ B 's would suffice if one could accumulate modes like $B^+ \rightarrow D^{+(*)} D^{0(*)}$.

1. Mechanism

The essence is two interfering amplitudes with two different kinds of phases.

Decay rate asymmetry between particle *vs.* antiparticle,

$$a_{CP} \equiv \frac{\Gamma(B \rightarrow f) - \bar{\Gamma}(\bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow f) + \bar{\Gamma}(\bar{B} \rightarrow \bar{f})}, \quad (1)$$

provides a measure of CP violation. However, CPT invariance demands the equality of the *total* rates,

$$\Gamma_{\text{tot}} = \bar{\Gamma}_{\text{tot}}. \quad (2)$$

Unitarity of the S -matrix then demands there be final state rescattering, or, presence of *absorptive parts*, as a necessary condition for CP violating rate asymmetries.

Define

$$\mathcal{M} = \mathcal{D} - \frac{i}{2}\mathcal{A}, \quad (3)$$

where $\mathcal{D}$ and $\mathcal{A}$ are the dispersive and absorptive (on-shell rescattering) amplitudes, respectively. With physical CP violating phases, such as KM (Kobayashi–Maskawa) model with 3 or more quark generations, $\mathcal{D}$ and $\mathcal{A}$ can both be complex. Hence, $\bar{\mathcal{M}} = \mathcal{D}^* - \frac{i}{2}\mathcal{A}^*$ for the process involving antiparticles, and we find

$$|\mathcal{M}|^2 = |\mathcal{D}|^2 + \frac{1}{4}|\mathcal{A}|^2 + \text{Im}(\mathcal{D}^*\mathcal{A}), \quad (4)$$

while for $|\bar{\mathcal{M}}|^2$, the $\mathcal{D}$ - $\mathcal{A}$ interference term changes sign. Suppressing phase space integration, *etc.* for simplicity, we have

$$a_{CP} = \frac{\text{Im}(\mathcal{D}^*\mathcal{A})}{|\mathcal{D}|^2 + \frac{1}{4}|\mathcal{A}|^2}. \quad (5)$$

It is therefore clear that, if $\mathcal{A} = 0$ (no absorptive part), or if $\mathcal{D}$ and $\mathcal{A}$ have *same* phase, then there can be no observable CP violating asymmetry.

1.1. Mixing Induced

B^0 - $\bar{B}^0$ mixing provides a fascinating vehicle for the above mechanism. Here, the dispersive part comes from direct decay, $\langle f|\mathcal{H}_W|B^0\rangle$, where f is usually chosen as an eigenstate of CP , while the absorptive part comes about via $\langle f|\mathcal{H}_W|\bar{B}^0\rangle\langle\bar{B}^0|4\text{-Fermi}|B^0\rangle$, *i.e.* mixing ($B^0 \rightarrow \bar{B}^0$) followed by decay of $\bar{B}^0$ to f . The two amplitudes clearly could have different CP violating phases. In other words, if one starts with B^0 at $t = 0$, the state could decay via $\mathcal{M}(B^0(t) \rightarrow f)$ or via $\bar{\mathcal{M}}(\bar{B}^0(t) \rightarrow f)$ at time t , assuming f is CP eigenstate. *The time dependent oscillation phase $e^{i\Delta m t}$ serves the function as absorptive part!* This is why mixing dependent CP asymmetries are so cute (quantum mechanics!) and clean: Δm is already measured and known, while the oscillation phase $e^{i\Delta m t}$ is to be measured directly, presumably by silicon based micro vertex detectors.

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The best known and best studied mode is $B^0 \rightarrow \psi K_S$, which would measure, without any hadronic “pollution”, the angle β (ϕ_1) of the 3 generation unitarity triangle. The mode has been under intense simulation study, for asymmetric B Factories at $\Upsilon(4S)$ energies, and for hadronic machines as well, both for fixed target and collider modes. Note that this mode has already been seen by CDF since 1990. With SVX installed, if the so-called “ B^{**} ” or “bachelor pion” tagging-via-production method works, there are some hopes that one may observe CP violation in this mode at the Tevatron collider, with Main Injector upgrade. Thus, this mode has been the conventional bet, but, as we have seen, one *needs* 1) *TAGGING*, 2) *two vertices* (for sake of $t_1 - t_2$ measurement). And hereby lies the challenge for these type of modes. It should also be remembered that once one goes beyond this mode, the challenge increases.

1.2. Direct (in decay)

The two interfering amplitudes are now $\langle f | \mathcal{H} | B^0 \rangle$ and $\langle f | \mathcal{H}_{\text{strong}} | i \rangle \langle i | \mathcal{H}_W | B^0 \rangle$, where i is any possible decay final state that could rescatter to the particular final state f (not necessarily CP eigenstate). The effective Hamiltonian of the first term includes the so-called penguin operators, induced by an interplay of weak and strong interactions. For the second term, the physical processes are, for example $B \rightarrow K + n\pi$, $D\bar{D}K + n\pi$ *etc.*, rescattering via strong interactions into final states such as $K + n\pi$, $K\phi$ *etc.*. The mechanism was first applied to B system by Bander, Silverman and Soni (BSS) [1]. The cute point is that strong interaction rescattering in the perturbative regime is readily incorporated in penguin absorptive parts via perturbative QCD, and by assuming duality, namely, that quark-gluon picture corresponds to the sum over all possible hadronic states. However, for the experimentally more tangible exclusive processes, both perturbative and *nonperturbative* strong phases enter, making them rather “unclean”. This is why these type of modes, in contrast to mixing-dependent ones, have received scant conventional bets.

These modes should not be overlooked, however, since they could be *discovery* modes. The

main advantage is that they are typically self-tagging and could be observed for both B^+ and B^0 decays. A symmetric B Factory would suffice. Besides theoretical uncertainties, the main experimental challenge is to log the data down (trigger problem for hadronic machines), and have good (charge and) K/π identification.

2. Direct CP Violation

Since there has been much devoted work and discussions in the past already, the purpose here is to summarize the salient features and point out theoretical and experimental problems/challenges.

2.1. Inclusive $b \rightarrow s$ and $b \rightarrow d$

It was by studying inclusive charmless B decays that Gérard and Hou [2] uncovered the full importance of CPT invariance and unitarity.

At the tree level, one has only $b \rightarrow su\bar{u}$ (one could always replace the s by d). There can be no CP asymmetries because there is only one amplitude and there is no rescattering. At $\mathcal{O}(\alpha_s)$, the tree level (dispersive) $b \rightarrow su\bar{u}$ amplitude can interfere with

$$\overbrace{b \rightarrow sc\bar{c}}^{\text{Weak}} \xrightarrow{\text{Strong}} sg^* \rightarrow su\bar{u} \quad (6)$$

which is absorptive. The physical $sc\bar{c}$ final state could rescatter inelastically via strong interactions. The beauty is, assuming the validity of perturbative QCD, this rescattering amplitude is given by calculating the absorptive part of the one-loop penguin amplitude. The validity of perturbative QCD is justified by the fact that the $c\bar{c}$ has to disappear into $u\bar{u}$, hence the q^2 of the $u\bar{u}$ pair is necessarily above $4m_c^2$.

The virtual gluon, however, can go into $d\bar{d}$ and $s\bar{s}$ as well. Furthermore, the penguin amplitude itself has dispersive contributions that mediate $b \rightarrow sq\bar{q}$ transitions. It turns out that, because the dominant $c\bar{c}$ and $t\bar{t}$ (virtual) states are not Cabibbo suppressed compared to usual b decay, while tree level $b \rightarrow su\bar{u}$ is multiply Cabibbo suppressed, the loop-induced penguin amplitude is stronger than the tree level dispersive amplitude

Table 1

(Semi-)inclusive BR and asymmetries for $b \rightarrow s$ and $b \rightarrow d$ processes, for $\rho = -0.5$, $\eta = 0.15$ and $m_t = M_W$. The dependence on m_t is weak, while dependence on ρ is more involved, but the asymmetries roughly scale linearly with η . Hence, if $\eta = 0.3$, the asymmetries are typically twice as large. $a(a_0)$ is with(out) the extra $\alpha_s^0 \cdot \alpha_s^2$ interference term taken into account. “0.0” stands for a very small positive number.

	BR (%)	a_0 (%)	a (%)
$b \rightarrow su\bar{u}$	0.46	1.2	0.0
$b \rightarrow sdd\bar{d} + ss\bar{s}$	0.54	0.5	0.5
Total Charmless $b \rightarrow s$	1.19	0.7	0.2
$b \rightarrow du\bar{u}$	0.71	-0.7	-0.0
$b \rightarrow ddd\bar{d} + ds\bar{s}$	0.07	-4.2	-4.2
Total Charmless $b \rightarrow d$	0.80	-1.0	-0.4
$b \rightarrow dc\bar{c}$	0.75	0.85	same

Adapted from: J.-M. Gérard and W.S. Hou, Phys. Rev. D **43**, 2909 (1991) [4].

in strength [3]. One therefore has an incentive to check and see whether the penguin decay by itself could exhibit CP asymmetries. Since the penguin process possesses both dispersive and absorptive contributions, and since all three generations contribute via this loop process, indeed, penguin–penguin interference could lead to CP violating asymmetries in pure penguin rates [1]. This, however, occurs at $\mathcal{O}(\alpha_s^2)$. Hereby lies the subtlety. Because of demands of CPT/unitarity, and, perhaps more important, the proximity of m_b to $c\bar{c}$ threshold, it turns out [2] that one not only has to include the effectively two-loop, $\mathcal{O}(\alpha_s^2)$ penguin–penguin interference CP violation effect, one has to incorporate another effectively two-loop, $\mathcal{O}(\alpha_s^2)$ effect due to tree–penguin interference where one has a cut on the virtual gluon line (absorptive part of gluon self-energy). In effect, the $\mathcal{O}(\alpha_s^2)$ term overwhelms the $\mathcal{O}(\alpha_s)$ term, which is counter-intuitive but is a truly subtle effect. For a detailed discussion, see ref. [4].

It suffices for our present purpose to see the numerical impact of the above discussion, which we display in Table 1. The $b \rightarrow dc\bar{c}$ mode will be discussed in Sec. 3. Experimentally it remains to be seen whether one can sum over modes to study inclusive asymmetries in a realistic way.

Note that since the a_{CP} in pure penguin modes $b \rightarrow sdd\bar{d}$, $ss\bar{s}$ are already at $\mathcal{O}(\alpha_s^2)$, they are unaffected by the additional $\mathcal{O}(\alpha_s^2)$ tree–penguin interference. However, admittedly, the effect of in-

corporating this extra $\mathcal{O}(\alpha_s^2)$ term on the $b \rightarrow su\bar{u}$ mode is rather dramatic. The fact that the effect is similar for $b \rightarrow d$ transitions means that the mechanism does not depend on KM structure. One other point: $b \rightarrow d$ type penguins possess much larger a_{CP} 's than $b \rightarrow s$ type penguins. This would carry over to the exclusive case, to which we now turn.

2.2. Exclusive Modes: Model Dependence

The problem here lies with theory: One needs to calculate hadronic matrix elements of 4-quark operators, just to evaluate decay rates. Despite advances due to Heavy Quark Effective Theory, because charmless final states always involve light hadrons, this is still something of an art form. We shall use the so-called BSW (Bauer–Stech–Wirbel) model.

For the evaluation of a_{CP} , which in addition depends on absorptive parts, there are two further basic questions/problems.

1. What is q^2 of virtual gluon?

For inclusive processes, q^2 is one of the phase space integration variables, and it is a fair approximation to assume perturbative QCD. For exclusive processes, the meson $B(b\bar{q}')$ decays into $s\bar{q}q\bar{q}'$, and typically $s\bar{q}$ forms a K , K^* , ϕ etc., while $q\bar{q}'$ forms π , ρ , K , K^* , etc.. Then q^2 would nominally correspond to the invariant mass squared of the $q\bar{q}$ pair. It is not clear what it actu-

Table 2

Summary table for penguin-related exclusive modes (illustrative) of interest.

Inclusive (quark)	Exclusive (hadron)	BR	a_{CP}
$b \rightarrow su\bar{u}$	$B^0 \rightarrow K^+\pi^-, K^{*+}\pi^-$		$\sim -2\% - +2\%$
{tree $\oplus$ penguin}	$B^+ \rightarrow K^+\rho^0, K^{*0}\pi^+$	$\mathcal{O}(10^{-5})$	(perturbative phase) $\sim -15\% - +15\%$ (w/ soft isospin phases)
$b \rightarrow ss\bar{s}$	$B \rightarrow K\phi, K^*\phi$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(1\%)$
{pure penguin}			
$b \rightarrow ds\bar{s}$	$B^+ \rightarrow K^+\bar{K}^{0*}, K^+K_S$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(\text{few} - 30)\%$
{pure $b \rightarrow d$ penguin}			
$b \rightarrow dc\bar{c}$	$B^+ \rightarrow D^{(*)}\bar{D}^{0(*)}$	$\mathcal{O}(0.02\% - 0.11\%)$	$\mathcal{O}(1\%)$
{tree $\oplus$ penguin}			(perturbative phase)

Adapted from: J.-M. Gérard and W.S. Hou, [4,6], and I. Dunietz and W.S.

Hou, [7].

ally means. On one hand, one may argue that the short distance rescattering should be summed over. One therefore may be tempted to take a_{CP} from the inclusive result of Table 1. On the other hand, one observes that the $q\bar{q}$ pair has to be more or less back-to-back and of high momentum to end up in a two-body meson final state. Furthermore, the spectator $\bar{q}'$ has to receive a kick to be sped up as well. From these lines of arguments, Gérard and Hou argue that the effective q^2 should be in the range $m_b^2/4 < q^2 < m_b^2/2$ [2].

The issue remains unsettled, and is symptomatic of the main problem for direct CP violation observables as opposed to mixing related ones: one does not have good control of the participating absorptive parts.

There is one recent development that is worthy of note, however. Akhoury, Sterman and Yao [5] have recently applied perturbative QCD with Sudakov suppression for a serious, “first principle” evaluation of $B \rightarrow \pi\pi$ decay rate. Working further along this line may shed some light on the issue of absorptive parts and effective q^2 value for two body decays.

2. Soft phases for $b \rightarrow su\bar{u}$ exclusive modes.

The $b \rightarrow su\bar{u}$ type of modes are special

in that they have both tree and penguin contributions. The former has isospin 0 and 1 components while the latter is purely isospin 0 (in the transition). Because of presence of two isospin amplitudes, unlike the pure penguin case, *soft* strong interaction phases are very important at the exclusive level [4]. At 5 GeV center of mass energy, these soft strong rescattering phases are not known and it is not clear whether they would ever be measurable.

With these comments, we present some numerical results in Table 2 as illustration for the range of “predictions”, and thereby the uncertainties involved. The $b \rightarrow dc\bar{c}$ entry would be discussed in next section.

When comparing with the standard mixing-dependent $B \rightarrow \psi K_S$ mode, some easily overlooked prejudices should be removed. The branching ratio of $\text{few} \times 10^{-4}$ and advertised asymmetries of order 10 – 50% both seem large in comparison. However, when the branching of $\psi \rightarrow \ell^+\ell^-$ and $K_S \rightarrow \pi^+\pi^-$ are folded in, the usable branching ratio is again of order 10^{-5} . At the same time, to observe $a_{CP} \sim 10 - 50\%$ one needs to reconstruct *both* vertices (double vertices) and tagging the b flavor.

Let us conclude the discussion of exclusive charmless B decays with the following observations:

- $b \rightarrow ds\bar{s}$ pure penguins (e.g. $B^+ \rightarrow K^+ K_S, K^+ \bar{K}^{0*}$)

Despite having the smallest branching ratios, we believe these are the most promising direct CP violation modes in the Standard Model [6]. With $\text{BR} \sim \text{few} \times 10^{-6}$ and a_{CP} potentially as large as 20 – 30%, $\mathcal{N}_B \geq \text{few} \times 10^7$ could suffice for each mode (here $\mathcal{N}_B$ stands for number of B 's needed). Moreover, since pure penguin modes have only one isospin component, one can sum over modes without suffering cancellations. If the inclusive results of Table 1 can be of any guide, *theoretically, with $\eta \sim 0.3$, a few $\times 10^6$ B 's could already suffice!* One should therefore put some premium on searching for these very rare loop-induced decays.

- $b \rightarrow su\bar{u}$ (e.g. $B^+ \rightarrow K^+ \pi^0, B^0 \rightarrow K^+ \pi^-$)

The branching ratio is at the 10^{-5} level. CLEO had the first glimpse of these modes in 1993, although they are not yet separable from $\pi\pi$. The key point here is that difference in soft phases between the two isospin amplitudes may make $|a_{CP}|$ as large as 15% [4]. Thus, again, $\mathcal{N}_B \geq \text{a few} \times 10^7$ could suffice to uncover CP violating asymmetries for a particular mode. However, the same reason that soft phases enter, if they are sizable at all, guarantees large cancellations when one attempts at accumulating different modes. That is, if the asymmetries per mode can be as large as 10%, it is necessarily due to soft phase differences, but then a_{CP} would necessarily fluctuate from mode to mode. It may also happen that the two isospin components receive similar soft phases, then one would again have per cent level asymmetries and $\mathcal{N}_B \geq 10^9$. One should therefore try hard for every possible mode, but attempts at summing over different modes would be in vain.

- $b \rightarrow ss\bar{s}$ pure penguin (e.g. $B^+ \rightarrow K^+ \phi$)

With $\text{BR} \sim 10^{-5}$ and $a_{CP} \leq 1\%$, we expect $\mathcal{N}_B \geq 10^9$ and Standard Model predicts no realistically observable CP asymmetry

in these modes. However, this is a consequence of small 3 generation CP violating phase that enters via the penguins. In case 3 generation unitarity is violated in any significant way, new physics effects could show up as $a_{CP} > 1\%$.

- Experimental relevance: Discovery Modes

Note that all of the above modes lead to final states constituting of 2 – 4 K or π mesons (or more). That is,

$$\left\{ \begin{array}{l} \pi\pi\pi, \pi\pi\pi\pi, \\ K\pi, K\pi\pi, K\pi\pi\pi, \\ K\bar{K}, K\bar{K}\pi, K\bar{K}\pi\pi, \\ KK\bar{K}, KK\bar{K}\pi, \text{ etc.}, \end{array} \right. \quad (7)$$

where $\pi\pi$ may form K_S or ρ , $K\pi$ may form K^* , while $K\bar{K}$ may be ϕ , etc. Direct, non-resonant decays into final states given in eq. 7 may be prominent. However, effective two body modes may be more realistic in suppressing combinatoric background.

Hence, to study direct CP violation effects, one needs good particle identification, i.e. K/π separation for the full momentum range. For asymmetric B Factories proposed at KEK and SLAC, this is up to momentum of 4 GeV/c or so. One should remember that, although good K/π separation is not needed for the most famous $B \rightarrow \psi K_S$ mode, they are again crucially needed for other types of mixing-dependent modes such as $B_d^0 \rightarrow \pi^+ \pi^-$ (suppression of $K\pi$ penguin). They are likewise needed for the method proposed by Gronau and Wyler [8] to measure $\gamma(\phi_2)$ by studying $B \rightarrow DK$.

3. Another Kind of Charmless: $b \rightarrow dc\bar{c}$ [7]

Traditionally, charmless final states refer to those with no charm particles whatsoever. A second type of “charmless” final state would be those that *have* charm particles, but coming in conjugate pairs so total charm quantum number $C = 0$. The strong interaction clearly can reshuffle these two classes of charmless final states. Indeed, we have seen previously that $b \rightarrow sc\bar{c} \rightarrow sg^* \rightarrow su\bar{u}$

rescattering to be a source of absorptive part. Here, we have the opposite. The tree level (dispersive) $b \rightarrow dc\bar{c}$ amplitude can interfere with

$$\overbrace{b \rightarrow du\bar{u}}^{\text{Weak}} \rightarrow \underbrace{dg^* \rightarrow dc\bar{c}}_{\text{Strong}} \quad (8)$$

which is absorptive. The physical $du\bar{u}$ final state could rescatter inelastically via strong interactions. We pick $b \rightarrow d$ penguins since, as we have seen earlier, they have more favorable KM phase combinations.

3.1. Illustrative estimate

Let us make a schematic estimate of the ensuing branching ratios and rate asymmetries. We have $B^\pm$ decay in mind, since for B^0 decay, the $d\bar{c}cd$ final state is self-conjugate. Note that there is only one single isospin amplitude. The tree level $b \rightarrow dc\bar{c}$ amplitude dominates the decay, and has the KM factor

$$v_c = V_{cd}^* V_{cb} \simeq -A\lambda^3, \quad (9)$$

where we have used the Wolfenstein parametrization. Taking the remaining tree amplitude as unity (and real), we need only the rescattering, therefore imaginary, amplitude of process given in eq. 8. This has the KM factor

$$v_u = V_{ud}^* V_{ub} \simeq A(\rho - i\eta)\lambda^3. \quad (10)$$

The remainder of the amplitude is $\mathcal{O}(\alpha_s)$ $u\bar{u} \rightarrow g^* \rightarrow c\bar{c}$ rescattering. Since q^2 is way above $c\bar{c}$ threshold, the amplitude can be taken as purely absorptive and therefore purely imaginary. Altogether one has $-i\alpha_s/4\pi$. Ignoring operator differences, the amplitude for B^- decay is

$$\mathcal{M} \propto -A\lambda^3 \left[1 + (\rho - i\eta) \frac{\alpha_s}{4\pi} i \right], \quad (11)$$

while for B^+ decay, η -term changes sign. We thus find

$$\text{BR}(b \rightarrow dc\bar{c}) \simeq \left| \frac{V_{cd}}{V_{cs}} \right|^2 \text{BR}(b \rightarrow sc\bar{c}), \quad (12)$$

$$a_{CP} \simeq \frac{|\mathcal{M}|^2 - |\bar{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\bar{\mathcal{M}}|^2} \simeq \frac{\alpha_s}{4\pi} (2\eta) \sim 1\%, \quad (13)$$

where we have taken $\alpha_s/4\pi \simeq 0.02$ and $2\eta \sim 0.5$. The branching ratio relation of eq. 12 should hold for both inclusive and exclusive modes.

We emphasize that the rate is tree dominant. Since $b \rightarrow sc\bar{c}$ modes have already been seen, the BR estimates are rather reliable. The a_{CP} estimate is also reliable since one is certainly in the perturbative domain. Note that although BR is much larger for $b \rightarrow sc\bar{c}$, the accompanying a_{CP} is smaller by λ^2 , of order 0.05%, way too small for sake of observation. Exclusively, one needs to study, for example, $B^- \rightarrow D^{0(*)} D^{-(*)}$ vs. $B^+ \rightarrow \bar{D}^{0(*)} D^{+(*)}$. Scaling from observed $B \rightarrow D^{(*)} \bar{D}_s^{(*)}$ branching ratios, one finds $\text{BR}(B \rightarrow D^{(*)} \bar{D}_s^{(*)})$ ranges from 0.02% to 0.11%, which agrees with model estimates. The BR and asymmetry estimates are listed also in Table 2. The crucial point, however, is probably distinguishing D from D_s , since full reconstruction of both D mesons would be rather punishing.

3.2. Inclusive: further illustration

We could use the inclusive results of Sec. 2.1 to further illustrate the point. The theoretical estimates for inclusive $b \rightarrow dq\bar{q}$ ($q \neq c$) is more reliable than the correspondings exclusive modes. Since the strong interaction mediates $q\bar{q} \leftrightarrow c\bar{c}$ rescattering, by CPT and unitarity arguments

$$\Delta\Gamma_{b \rightarrow dq\bar{q}} = -\Delta\Gamma_{b \rightarrow dc\bar{c}} \quad (14)$$

that is, the increase(decrease) in inclusive $b \rightarrow dq\bar{q}$ rate corresponds to decrease(increase) in $b \rightarrow dc\bar{c}$ rate. Strong interaction just reshuffles among the modes. Thus, from Table 1,

$$\begin{aligned} \Delta\text{BR}_{q\bar{q}} &= -\Delta\text{BR}_{c\bar{c}} \\ &= \text{BR}(b \rightarrow dq\bar{q}) \cdot a(b \rightarrow dq\bar{q}) \\ &\simeq 0.8\% \cdot (-0.8\%), \end{aligned} \quad (15)$$

where, in the last step we have assumed $\eta = 0.3$ rather than the value of 0.15 used in Table 1. From

$$\text{BR}(b \rightarrow dc\bar{c}) \simeq \lambda^2 \text{BR}(b \rightarrow sc\bar{c}) \sim 0.75\%, \quad (16)$$

we find

$$a(b \rightarrow dc\bar{c}) \simeq \frac{0.64 \times 10^{-4}}{0.75 \times 10^{-2}} \simeq 0.85\%. \quad (17)$$

These results are also listed in Table 1. Note that the asymmetry is basically unaffected by two-loop effects. Thus, at the 3σ level, in principle

$$\mathcal{N}_B \sim 9 \text{BR}^{-1} a_{CP}^{-2} \geq 2 \times 10^7 \quad (18)$$

B mesons would suffice for uncovering CP violation in $b \rightarrow dc\bar{c}$ modes. The question is whether one could develop methods for inclusive study. Again, one has to eliminate $b \rightarrow sc\bar{c}$ “background”, which has vanishingly small asymmetry but BR at 15% level.

Note that a second source for CP violation is possible: $b\bar{u}$ annihilates into $d\bar{u}$, pulling out $c\bar{c}$ from QCD vacuum. The annihilation diagram, however, cannot be reliably calculated, and is likely very small.

The cleanliness of $b \rightarrow (d \text{ or } s)c\bar{c}$ for CP violation studies was already mentioned by BSS, was followed up by Chau and Cheng [9], and can be found in a recent work by Simma and Wyler [10]. However, these modes have not been stressed in the literature since the late 1980’s. Somehow, the uncovering of subtleties in $b \rightarrow (d \text{ or } s)q\bar{q}$ modes has had the side effect of suppressing the $b \rightarrow (d \text{ or } s)c\bar{c}$ modes from public consciousness. It needs to be re-emphasized so experimenters can be prepared when B Factories turn on. If one reconstructs the D ’s, with good tracking and momentum resolution, one has less demands on particle identification. Perhaps one can then profit from the high production cross section at hadronic machines.

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