

CP asymmetries in (semi-)inclusive B^0 decays

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Abstract. It was recently pointed out that inclusive $B^0(t)$ decays could show mixing-induced CP violation. The totally inclusive asymmetry is expected to be tiny [$\mathcal{O}(10^{-3})$] because of large cancellations among the asymmetries in the charmless, single charm and double charm final states. Enriching particular final state configurations could significantly increase the CP-asymmetry and observability. Such studies can extract fundamental CKM (Cabibbo-Kobayashi-Maskawa) parameters, and (perhaps) even $\Delta m(B_s)$. A superb vertex detector could see CP violation with 10^5 (10^6) flavor-tagged B_s (B_d) mesons within the CKM model. Because the effects could be significantly larger due to new physics, they should be searched for in existing or soon available data samples.

1 Introduction

CP violation remains a mystery more than 30 years after its discovery [1]. It has been observed so far only in K^0 decays. Our entire knowledge can be summarized by the single CP-violating quantity [2]

$$\begin{aligned} \epsilon &= A(K_L \rightarrow 2\pi)/A(K_S \rightarrow 2\pi) \\ &= 2.28 \times 10^{-3} \times e^{i\pi/4}. \end{aligned} \quad (1.1)$$

CP violation is not just a quaint, tiny effect in K^0 decays, but is necessary for baryogenesis [3]. The origin of CP violation has not yet been established. A fundamental understanding of CP violation will bring about a deeper appreciation of our existing universe. The fashionable CKM hypothesis [4] allows for one CP-violating phase which is fitted to the single observed quantity ϵ . In contrast, other aspects of the Standard Model have been subjected to many independent tests and have been verified to high precision [2]. Fortunately, the CKM hypothesis is testable and predicts large CP-asymmetries in many B decays [5], for instance [6]

$$\text{Asym}(B_d \rightarrow J/\psi K_S) \gtrsim 20\%. \quad (1.2)$$

The traditional efforts focused on the gold-plated $B_d \rightarrow J/\psi K_S$ or other exclusive B -modes. While the CP-asymmetry is predicted to be large, the effective branching ratio is tiny ($\sim 10^{-5}$). Orders of magnitude larger branching ratios are available from studies of (semi-) inclusive CP-asymmetries [7–12],

$$I(t) \equiv \frac{\Gamma(B^0(t) \rightarrow \text{all}) - \Gamma(\bar{B}^0(t) \rightarrow \text{all})}{\Gamma(B^0(t) \rightarrow \text{all}) + \Gamma(\bar{B}^0(t) \rightarrow \text{all})}. \quad (1.3)$$

Such an inclusive asymmetry appears to violate the CPT theorem, which guarantees equal total widths for

particle and antiparticle. This theorem may have discouraged experimenters to search for CP effects in their large, inclusive B -samples. There is no contradiction with the CPT theorem, however. $B^0 - \bar{B}^0$ mixing introduces an additional amplitude, which permits the time-dependent totally inclusive rate to differ from its CP-conjugated partner. The only constraint provided by the CPT theorem is that

$$\int_0^\infty dt \Gamma(B^0(t) \rightarrow \text{all}) = \int_0^\infty dt \Gamma(\bar{B}^0(t) \rightarrow \text{all}). \quad (1.4)$$

For a *truly* unbiased B^0 sample, the time-dependence is known [9, 11],

$$I(t) = a \left[\frac{x}{2} \sin \Delta m t - \sin^2 \left(\frac{\Delta m t}{2} \right) \right]. \quad (1.5)$$

Here the mixing parameter $x \equiv \Delta m/\Gamma$. The width-difference $\Delta\Gamma$ is neglected throughout this report, and a is the conventional dilepton asymmetry [13],

$$\begin{aligned} a &\equiv \text{Im}(\Gamma_{12}/M_{12}) \\ &= - \frac{\Gamma(B^0(t) \rightarrow W) - \Gamma(\bar{B}^0(t) \rightarrow \bar{W})}{\Gamma(B^0(t) \rightarrow W) + \Gamma(\bar{B}^0(t) \rightarrow \bar{W})}. \end{aligned} \quad (1.6)$$

Here W stands for a flavor-specific \bar{B}^0 mode, i.e. that cannot be accessed from an unmixed B^0 , such as $\ell^- X$.

The observable a is expected to be tiny [$\sim 10^{-3}$ ($\lesssim 10^{-4}$) for B_d (B_s) mesons] [14, 15]. Much larger CP violating effects are expected in each of the semi-inclusive $b \rightarrow q$ (charmless), \bar{c} (single charm), $c\bar{c}$ (double charm) transitions [9]. The semi-inclusive asymmetries are opposite in sign and largely cancel when combined to form the

Table 1. Branching ratios and efficiencies as a function of charm content in inclusive \overline{B}^0 decays

Process	Branching Ratio	Efficiency
$b \rightarrow \not{c}$ (charmless)	0.07	ϵ_0
$b \rightarrow \overline{c}^{(-)}$ (single charm)	0.74	ϵ_1
$b \rightarrow c\overline{c}$ (double charm)	0.19	ϵ_2

totally inclusive asymmetry a . A superb vertex detector could select each of the semi-inclusive transitions, thereby becoming sensitive to CP violating effects that are predicted to be significantly enhanced. The selection could be done continuously by varying the efficiencies ϵ_i for recording the specific transitions (see Table 1). The efficiencies to observe charmless, single charm, double charm final states are denoted by ϵ_0 , ϵ_1 , ϵ_2 , respectively. Because vertexing alone cannot distinguish B^0 modes involving hidden charmonia from truly non-charm final states, both are classified as charmless modes in this note.

This report assumes identical detection efficiency for mode ϵ_i and CP-conjugated mode $\bar{\epsilon}_i$,

$$\epsilon_i = \bar{\epsilon}_i. \quad (1.7)$$

The assumption may not hold because the detector is made out of matter and because of possible asymmetries in reconstructing positive versus negative tracks. Since those are detector-specific issues, they will not be considered further in the main text (see, however, Appendix A), but have to be investigated by each experiment.

The efficiencies can be varied continuously by suitable cuts, thereby “biasing” or “weighting” the inclusive asymmetry (1.3) and making it dependent on ϵ_i ,

$$I(t) = -a \sin^2\left(\frac{\Delta mt}{2}\right) + c \sin \Delta mt. \quad (1.8)$$

Here a is the dilepton asymmetry defined in (1.6) and is independent of ϵ_i , while the coefficient c depends on ϵ_i . Both coefficients a and c are functions of CKM parameters and are given in Appendix B¹. Alternatively, one could assign to each inclusive B^0/\overline{B}^0 decay a probability for being a charmless, single charm or double charm transition, thereby “weighting” the inclusive asymmetry. The coefficient a is independent on this “weighting”, while the coefficient c depends on it.

For identical detection efficiencies $\epsilon_i = \epsilon$, Appendix B obtains $c = a \cdot x/2$ and the truly inclusive asymmetry is recovered. Further note that in general a time-integrated CP violating asymmetry survives, since c normally differs from $a \cdot x/2$. This realization permits us to search for *time-integrated* CP violating effects in single or double charm or charmless samples.

¹ It is now clear how to extract the efficiency-independent observable a from time-dependent and efficiency-varying studies. The extraction can be accomplished even for a non-vanishing width difference $\Delta\Gamma$. The formalism is straightforward, just somewhat more cumbersome [9].

Table 2. The coefficient c and required number of tagged $B_s + \overline{B}_s$ mesons to observe a 3σ CP violating effect as a function of the efficiencies ϵ_i . The $B_s - \overline{B}_s$ mixing parameter was chosen as $x_s = 30$, the CKM parameters as $\rho = 0, \eta = 0.4$, and the CP violating parameter a was neglected. The values inside the curly parentheses assume that the double charm asymmetry is the same for the (hidden $c\overline{c}$) sector and for the (open $c + \text{open } \overline{c}$) channels. The values in front of the curly parentheses assume that the entire double charm (c quark + \overline{c} antiquark) asymmetry resides in (open $c + \text{open } \overline{c}$) channels, and that there is no asymmetry in the (hidden $c\overline{c}$) sector. (See Appendix B for details)

ϵ_0	ϵ_1	ϵ_2	c	$[N_{B_s} + N_{\overline{B}_s}](3\sigma)$
1	0	0	0 $\{-0.015\}$	$\infty \{1 \times 10^6\}$
0	1	0	0.007	6×10^5
0	0	1	-0.023 $\{-0.017\}$	$2 \times 10^5 \{3 \times 10^5\}$

Table 3. The coefficient c and required number of tagged $B_d + \overline{B}_d$ mesons to observe a 3σ CP violating effect as a function of the efficiencies ϵ_i . The CKM parameters were chosen as $\rho = 0, \eta = 0.4$, and the CP violating parameter a was neglected. The values inside the curly parentheses assume that the double charm asymmetry is the same for the (hidden $c\overline{c}$) sector and for the (open $c + \text{open } \overline{c}$) channels. The values in front of the curly parentheses assume that the entire double charm (c quark + \overline{c} antiquark) asymmetry resides in (open $c + \text{open } \overline{c}$) channels, and that there is no asymmetry in the (hidden $c\overline{c}$) sector. (See Appendix B for details)

ϵ_0	ϵ_1	ϵ_2	c	$[N_{B_d} + N_{\overline{B}_d}](3\sigma)$
1	0	0	-0.005 $\{0.0010\}$	$2 \times 10^7 \{4 \times 10^8\}$
0	1	0	-0.0021	8×10^6
0	0	1	0.009 $\{0.007\}$	$2 \times 10^6 \{3 \times 10^6\}$

Our current knowledge about the CKM matrix in the Wolfenstein representation [16] can be parameterized as follows [15,17]

$$-0.3 < \rho < 0.3, \quad 0.2 < \eta < 0.5.$$

The effect on c of varying ρ is not too significant, whereas varying η has a more drastic effect (see Appendix B).

Choose $\rho = 0$ and $\eta = 0.4$ for illustrative purposes. As a function of efficiencies ϵ_i , Tables 2 and 3 list the CP-violating coefficient c . The last column shows how many tagged B^0 [N_{B^0}] and tagged \overline{B}^0 [$N_{\overline{B}^0}$] have to be produced to observe c to 3σ accuracy (with a neglected). Here tagging denotes the distinction of an initial B^0 and \overline{B}^0 . A superb vertex detector could observe inclusive CP-violation with 10^5 (10^6) tagged B_s (B_d) mesons. Because the specific efficiencies ϵ_i can be varied continuously, many systematic effects can be controlled and studied. For a given detector, the optimal choice for $\epsilon_0, \epsilon_1, \epsilon_2$ can be determined, by minimizing the required produc-

tion of tagged B^0 and tagged \bar{B}^0 mesons to observe a 3σ asymmetry $[N_{B^0} + N_{\bar{B}^0}](3\sigma)$.

A nonzero coefficient $c(B_s) \neq 0$ ($a(B_s) \neq 0$), would prove CP violation in the B_s sector and further would permit an unconventional determination of $\Delta m(B_s)$ (from flavor-nonspecific final states). In contrast, conventional methods require the \bar{B}_s to be seen in flavor-specific modes, such as $D_s^+ X \ell^- \bar{\nu}$, $D_s^+(\pi, \rho, a_1)^-$ [18, 19].

The double charm \bar{B}_d modes are promising, and have a predicted semi-inclusive asymmetry of $\mathcal{O}(1\%)$ (see Table 3). The CP signal is due to the Cabibbo suppressed $b \rightarrow c\bar{c}d$ transitions [9], and is unfortunately diluted by the ~ 20 times larger Cabibbo-allowed $b \rightarrow c\bar{c}s$ processes. The generic \bar{B}_d decays governed by $b \rightarrow c\bar{c}s$ give rise to flavor-specific final states which cannot be reached from both an unmixed B^0 and an unmixed \bar{B}^0 , and therefore are not sensitive to the mixing-induced CP violating effects discussed in this note.

One can either attempt to enrich the $b \rightarrow c\bar{c}d$ transitions over the $b \rightarrow c\bar{c}s$ processes via particle identification, or one could cause the modes governed by $b \rightarrow c\bar{c}s$ to be accessible from both a B^0 and a \bar{B}^0 . The latter can be accomplished by having the primary s quark hadronize into a neutral kaon, which is then observed as a K_S or K_L ². More generally, \bar{B}^0 modes that involve a single primary s quark³ are normally flavor-specific. Nevertheless, mixing-induced CP violating effects are expected when that primary s quark is seen as a neutral K_S or K_L , as in the following B^0 modes:

$$\text{primary } K_{S(L)} + \left\{ \not{c}, \overset{(-)}{c}, c\bar{c} \right\}. \quad (1.9)$$

CP violation may be seen in inclusive K_S studies [either time-integrated or time-dependent]:

$$\frac{\Gamma(B_d(t) \rightarrow K_S X) - \Gamma(\bar{B}_d(t) \rightarrow K_S X)}{\Gamma(B_d(t) \rightarrow K_S X) + \Gamma(\bar{B}_d(t) \rightarrow K_S X)}. \quad (1.10)$$

Focusing on primary K_S 's ($B \rightarrow K_S$), which do not originate from intermediate charmed hadrons ($B \rightarrow \overset{(-)}{c} \rightarrow K_S$), may enhance the CP asymmetry [Eq. (1.10)] within the CKM model. The underlying transitions are essentially:

- $\bar{B}_d \rightarrow D\bar{D}K_S X$ [6, 8]
- $\bar{B}_d \rightarrow K_S X$ governed by penguin amplitudes, and
- $\bar{B}_d \rightarrow (c\bar{c})K_S X$, where the $(c\bar{c})$ pair annihilates non-perturbatively into light hadrons [20–22] or hadronizes as hidden charmonia [8].

² The CP effects involving primary K_S versus primary K_L are opposite in sign, and therefore should be combined carefully.

³ The s -quark produced in \bar{B}_d -transitions governed by $b \rightarrow c\bar{c}s$, $\bar{c}u\bar{s}$, $\bar{u}\bar{c}s$, s , or the spectator s -quark in B_s -transitions governed by $\bar{b} \rightarrow \bar{c}\bar{c}\bar{d}$, $\bar{c}u\bar{d}$, $\bar{u}\bar{c}\bar{d}$, \bar{d} .

These processes are governed essentially by the CKM combination $V_{cb}V_{cs}^*$. $B_d - \bar{B}_d$ mixing introduces the interfering amplitude $B_d(t) \rightarrow \bar{B}_d \rightarrow K_S X$, and CP violation could occur. Within the CKM model, that CP violating effect depends on the weak phase 2β . In addition to the observation of the primary K_S , other available information concerning the decay products of the B_d/\bar{B}_d should be incorporated, as that may increase further the CP violating effects.

While obviously very useful, superb vertexing is not mandatory for several studies advocated here. For instance, the time-integrated $B_d \rightarrow K_S X$ asymmetry (1.10) does not require superb vertex information. In addition, present techniques can enhance the double charm content by fully reconstructing one charmed hadron and inferring inclusively (via the soft charged pion in $D^* \rightarrow \pi^+ D$ processes, and/or via vertexing) the other in the same b -hemisphere. The existence of two charmed hadrons in the same b -hemisphere could be inferred more inclusively perhaps by combining vertex information with observed kaon yields. In contrast, charmed hadrons produced in single charm events differ in their momentum distribution and are likely more detached from the remainder of the b -decay than double charm events. Those and other available techniques could be used to enhance CP effects in existing or soon available data samples.

This note focuses on mixing-induced CP violation which requires tagging. Semi-inclusive B decays could show direct CP violation, which does not involve mixing-induced amplitudes and requires no tagging [23, 24]. The direct CP violating effects are expected to be tiny. If they are observed in charged B^\pm decays, then those B^\pm measurements can be incorporated straightforwardly into the general formalism of semi-inclusive B^0 asymmetries [9]. In addition to searching for quasi-inclusive direct CP violation involving charged *primary* $K^{(*)-}$ [24], mixing-induced CP effects could be looked for in tagged momentum-spectra of *secondary* $K^{(*)}$ [$B^0 \rightarrow \overset{(-)}{c} \rightarrow K^{(*)}$] [12, 25]. The single charm/double charm content can be varied somewhat by varying the $K^{(*)}$ momenta.

What is the current experimental status? The DELPHI and SLD collaborations [26, 27] implicitly assumed an unbiased inclusive B sample. By fitting their data to the known unique time-dependence (1.5), they extracted the observable a for the B_d meson

$$a_d = \begin{cases} -0.022 \pm 0.030 \pm 0.011 & \text{DELPHI} \\ -0.04 \pm 0.12 \pm 0.05 & \text{SLD} \end{cases} \quad (1.11)$$

Their data samples are probably biased, however (see Appendix C). Because in addition, the predicted a is tiny [14, 15] it is instructive to fit the measurements to $\sin \Delta mt$ ⁴. If CP is conserved, the inclusive, time-dependent asymmetry vanishes and cannot show any Δmt -dependence. In real life, however, a residual Δmt -dependence

⁴ Current data [26, 27] are incapable of discriminating among a wide variety of possible interpretations. On the other hand, the existing data do not rule out a $\sin \Delta mt$ -dependence. We performed a single parameter fit to the DELPHI data [26] of

may be seen even in the absence of CP violation, because, for example, of different detection efficiencies for mode and CP-conjugated mode (see Appendix A).

Such “fake” CP-effects are less important when the expected CP violating signal is enhanced manifold. The enhancement can be accomplished by refined CP studies that consciously enrich specific non-leptonic transitions. While this note discussed enrichments of the charmless, single charm, and double charm sectors, the idea is clearly much more general. As more insights into B decays are gained, suitable cuts or weighting factors can be designed for each of the sectors to further enhance CP violation, for instance, by increasing CP-even over CP-odd configurations (or vice versa). Those enrichment techniques are in their early stages. Once they mature, observation of CP violation and quantitative extractions of CKM parameters become feasible [9]. That may prove useful, because CP violation is one of the most important mysteries in high energy physics.

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Appendix A: On faking CP violation

Because current B decay simulations may have to be modified (see Appendix C), slight differences in acceptance and detection efficiencies of mode f and CP-conjugated mode $\bar{f} \equiv CP f$ must be investigated further. Those differences arise because the detector is made out of matter where particle and antiparticle interact differently and because of possible asymmetries in reconstructing positive versus negative tracks. The differences are parameterized by the small deviation from 1 of the real quantity η in this appendix. This appendix assumes CP conservation throughout. A Δmt -dependence may still be seen, because (see (A1) top of the next page)

the form

$$I(t) = c \sin \Delta mt,$$

with $\Delta m = 0.474 \text{ ps}^{-1}$ [2], and obtained

$$c = 0.03 \pm 0.01.$$

Our two parameter fit for c and Δm yields

$$c = 0.03 \pm 0.01, \quad \Delta m = 0.5 \pm 0.1 \text{ ps}^{-1},$$

which correctly recovers the known $B_d - \bar{B}_d$ frequency Δm . The fits have a χ^2 per degree of freedom somewhat better than 1. The quoted errors are statistical only. Systematic uncertainties could be significantly larger.

The coefficients q and p relate the B^0 and \bar{B}^0 states to the mass eigenstates and satisfy $|q/p| = 1$ [28]. The interference terms $\lambda \equiv q\langle f|\bar{B}^0\rangle/(p\langle f|B^0\rangle)$ and $\bar{\lambda} \equiv p\langle \bar{f}|B^0\rangle/(q\langle \bar{f}|\bar{B}^0\rangle)$ satisfy $\lambda = \bar{\lambda}$ under the assumption of CP conservation. They could have a nonzero imaginary part only due to a final state phase difference [29,28]. (CP conservation demands vanishing weak phase differences!) (A1) can be traced back to the fact that a Δmt -dependence survives if the difference between f and \bar{f} has not been accounted for correctly ($\eta \neq 1$):

$$\begin{aligned} & \Gamma(B^0(t) \rightarrow f) + \eta \Gamma(B^0(t) \rightarrow \bar{f}) \\ &= \Gamma(B^0 \rightarrow f) \frac{e^{-\Gamma t}}{2} \left\{ (1 + \eta)(1 + |\lambda|^2) + (1 - \eta) \right. \\ & \quad \left. \times [\cos \Delta mt (1 - |\lambda|^2) - 2Im\lambda \sin \Delta mt] \right\}, \quad (A2) \end{aligned}$$

$$\begin{aligned} & \Gamma(\bar{B}^0(t) \rightarrow f) + \eta \Gamma(\bar{B}^0(t) \rightarrow \bar{f}) \\ &= \Gamma(B^0 \rightarrow f) \frac{e^{-\Gamma t}}{2} \left\{ (1 + \eta)(1 + |\lambda|^2) - (1 - \eta) \right. \\ & \quad \left. \times [\cos \Delta mt (1 - |\lambda|^2) - 2Im\lambda \sin \Delta mt] \right\}. \quad (A3) \end{aligned}$$

All Δmt -dependence is gone when mode and CP-mode are summed over “properly” ($\eta = 1$):

$$\begin{aligned} & \Gamma(B^0(t) \rightarrow f) + \Gamma(B^0(t) \rightarrow \bar{f}) \\ &= \Gamma(\bar{B}^0(t) \rightarrow \bar{f}) + \Gamma(\bar{B}^0(t) \rightarrow f) \\ &= \Gamma(B^0 \rightarrow f) e^{-\Gamma t} (1 + |\lambda|^2). \quad (A4) \end{aligned}$$

Thus, as long as mode and CP-mode are combined properly, no Δmt -dependence survives (A4). This is true whether or not there exists an unaccounted difference in tagging (distinguishing) an initial B^0 and \bar{B}^0 .

There exist methods that may reduce a possible small discrepancy of distinguishing an initial B^0 and \bar{B}^0 (for instance, by using polarized Z^0 s [30]). Nonetheless, we wish to present the expression which takes that discrepancy also into account. [The small deviation from 1 of the parameter τ quantifies the discrepancy here]: (see (A5) top of the next page) That concludes our discussion of some of the systematic effects that are CP conserving.

Appendix B: The (semi-)inclusive CP violating parameters

The time-dependence of the (semi-) inclusive CP violating asymmetry⁵,

$$I(t) = -a \sin^2 \left(\frac{\Delta mt}{2} \right) + c \sin \Delta mt, \quad (B1)$$

follows from the formalism outlined in [9,31]. The coefficient $a \equiv Im(\Gamma_{12}/M_{12})$ does not depend on the efficiencies

⁵ Neglecting $\Delta\Gamma$ and direct CP violation.

$$\begin{aligned} & \frac{\Gamma(B^0(t) \rightarrow f) + \eta \Gamma(B^0(t) \rightarrow \bar{f}) - \left\{ \Gamma(\overline{B}^0(t) \rightarrow f) + \eta \Gamma(\overline{B}^0(t) \rightarrow \bar{f}) \right\}}{\Gamma(B^0(t) \rightarrow f) + \eta \Gamma(B^0(t) \rightarrow \bar{f}) + \Gamma(\overline{B}^0(t) \rightarrow f) + \eta \Gamma(\overline{B}^0(t) \rightarrow \bar{f})} \\ &= (1 - \eta) \frac{[\cos \Delta mt (1 - |\lambda|^2) - 2Im\lambda \sin \Delta mt]}{(1 + \eta)(1 + |\lambda|^2)}. \end{aligned} \quad (\text{A1})$$

$$\begin{aligned} & \frac{\Gamma(B^0(t) \rightarrow f) + \eta \Gamma(B^0(t) \rightarrow \bar{f}) - \tau \left[\Gamma(\overline{B}^0(t) \rightarrow f) + \eta \Gamma(\overline{B}^0(t) \rightarrow \bar{f}) \right]}{\Gamma(B^0(t) \rightarrow f) + \eta \Gamma(B^0(t) \rightarrow \bar{f}) + \tau \left[\Gamma(\overline{B}^0(t) \rightarrow f) + \eta \Gamma(\overline{B}^0(t) \rightarrow \bar{f}) \right]} \\ &= \frac{(1 + \eta)(1 - \tau)(1 + |\lambda|^2) + (1 - \eta)(1 + \tau) [\cos \Delta mt (1 - |\lambda|^2) - 2Im\lambda \sin \Delta mt]}{(1 + \eta)(1 + \tau)(1 + |\lambda|^2) + (1 - \eta)(1 - \tau) [\cos \Delta mt (1 - |\lambda|^2) - 2Im\lambda \sin \Delta mt]} \\ &\approx \frac{(1 - \tau)(1 + |\lambda|^2) + (1 - \eta) [\cos \Delta mt (1 - |\lambda|^2) - 2Im\lambda \sin \Delta mt]}{2(1 + |\lambda|^2)}. \end{aligned} \quad (\text{A5})$$

ϵ_i but does depend on the CKM parameters [13]. In contrast, the parameter c depends both on ϵ_i and on CKM parameters,

$$c = \frac{x}{2} \frac{\sum_{f=0,1,2} \epsilon_f Im(\Gamma_{f,12}/M_{12})}{(\epsilon_0 B_0 + \epsilon_1 B_1 + \epsilon_2 B_2)}. \quad (\text{B2})$$

Here B_i ($i = 0, 1, 2$) denote the inclusive branching ratios (for $\ell, \bar{c}, c\bar{c}$ modes of an unmixed $B_{d,s}$), and are listed in Table 1. Note that $c = \frac{x}{2}a$ for $\epsilon_0 = \epsilon_1 = \epsilon_2$ because $\Gamma_{12} = \sum_{f=0,1,2} \Gamma_{f,12}$ [9]. What remains is to show how $\sum_f \epsilon_f Im(\Gamma_{f,12}/M_{12})$ depends on the fundamental CKM parameters and on other quantities.

We consider two scenarios for $B_{d,s}$ modes containing a c quark and a \bar{c} quark. Theory estimates the inclusive CP asymmetry for such modes [9]. Those modes consist of (open c + open \bar{c}) subchannels and (hidden $c\bar{c}$) subchannels. Scenario A assumes that both subchannels experience the same CP asymmetry, which therefore is taken to be the ‘‘calculated’’ (c quark + \bar{c} quark) asymmetry.

On the other hand, perturbative QCD favors a much suppressed asymmetry for the (hidden $c\bar{c}$) subchannels [32]. Scenario B assumes that the entire calculated (c quark + \bar{c} quark) asymmetry resides in the (open c + open \bar{c}) subchannels, with no asymmetry in (hidden $c\bar{c}$) processes.

The above distinction is important because the truly (no charm) and the (hidden $c\bar{c}$) modes both involve a single B decay vertex, which the main text denotes as charmless modes. Note further that the main text denotes the (open c + open \bar{c}) channels as $c\bar{c}$. The formalism yields:

$$\begin{aligned} & \sum_f \epsilon_f Im(\Gamma_{f,12}/M_{12}) \\ &= -\frac{\pi}{2} \frac{m_b^2}{M_W^2 \eta_B S_0(x_t)} \left\{ Im \left(\frac{\lambda_c}{\lambda_t} \right)^2 \right. \\ & \quad \times \left[\frac{\epsilon_2 B_2 + \epsilon_h B_h}{(B_2 + B_h)} F_2 - 2\epsilon_1 F_1 + F_0 \epsilon_0 \right] \end{aligned}$$

$$- 2Im \frac{\lambda_c}{\lambda_t} [\epsilon_1 F_1 - \epsilon_0 F_0] \left. \right\} \quad [\text{scenario A}] \quad (\text{B3})$$

$$\begin{aligned} &= -\frac{\pi}{2} \frac{m_b^2}{M_W^2 \eta_B S_0(x_t)} \left\{ Im \left(\frac{\lambda_c}{\lambda_t} \right)^2 \right. \\ & \quad \times [\epsilon_2 F_2 - 2\epsilon_1 F_1 + \epsilon_0 F_0] \\ & \quad \left. - 2Im \frac{\lambda_c}{\lambda_t} [\epsilon_1 F_1 - \epsilon_0 F_0] \right\} \quad [\text{scenario B}]. \end{aligned} \quad (\text{B4})$$

The QCD parameter $\eta_B = 0.8475$ and the $S_0(x_t) = 2.41$ function dependent on $x_t \equiv (m_t/M_W)^2$ are reviewed in [33]. The inclusive branching ratio [detection efficiency] into (hidden $c\bar{c}$) modes is denoted by B_h [ϵ_h]. This report assumes $\epsilon_h = \epsilon_0$. Because $B_{\text{no charm}} \approx 0.01$ and B_0 has a predicted central value of 0.07 [34], we chose $B_h = 0.06$ for illustrative purposes. Table 4 lists the relevant CKM combinations [$\lambda_k \equiv V_{kd}^* V_{kb}$ ($V_{ks}^* V_{kb}$) for \overline{B}_d (\overline{B}_s) mesons] in terms of the Wolfenstein parameters. The F_i ($i = 0, 1, 2$) are QCD corrected phase-space factors. Their leading order expressions in $1/m_b$ expansion are [31]

$$F_2 = \frac{\sqrt{1-4z}}{3} \{ 4[2(1-z)K_1 + (1-4z)K_2] + 5(1+2z)(K_2 - K_1) \}, \quad (\text{B5})$$

$$F_1 = \frac{(1-z)^2}{3} \{ 4[(2+z)K_1 + (1-z)K_2] + 5(1+2z)(K_2 - K_1) \}, \quad (\text{B6})$$

$$F_0 = \frac{1}{3} \{ 4(2K_1 + K_2) + 5(K_2 - K_1) \}, \quad (\text{B7})$$

where

$$z \equiv m_c^2/m_b^2.$$

The QCD coefficients were taken to be $K_1 = -0.3876$ and $K_2 = 1.2544$. In addition, the numerical estimates of Tables 2–3 used $m_b = 4.8 \text{ GeV}/c^2$ and $m_c = 1.4 \text{ GeV}/c^2$.

Table 4. Relevant CKM combinations in terms of the Wolfenstein parameters (η, ρ) . The Cabibbo angle is denoted by $\theta = 0.22$

	$Im(\lambda_c/\lambda_t)$	$Im(\lambda_c/\lambda_t)^2$
B_d	$\frac{\eta}{(1-\rho)^2+\eta^2}$	$\frac{-2\eta(1-\rho)}{[(1-\rho)^2+\eta^2]^2}$
B_s	$-\eta\theta^2$	$2\eta\theta^2$

Appendix C: Inclusive B -hadron decays

Inclusive B decays maybe more subtle than currently modeled. Thus, what is considered an unbiased inclusive B data sample may in reality be biased. This appendix questions the current modeling of sizable fractions of B decays, especially:

1. baryon production in B meson decays,
2. $\bar{B} \rightarrow DD \bar{K} X$ transitions,
3. $\bar{B} \rightarrow$ no open charm, and
4. $b \rightarrow c\bar{u}d$ transitions.

C.1 $B \rightarrow$ baryons

Models conventionally assume that a weakly decaying charmed baryon is produced in generic $B \rightarrow$ baryons transitions [35]. However, a straightforward analysis predicts that $\bar{B} \rightarrow DN\bar{N}'X$ processes may be a sizable fraction of all $B \rightarrow$ baryons transitions, where $N^{(\prime)}$ denotes a nucleon [36,34]. While the Ξ_c yield in B decays had been neglected initially [35], its current central value [37] is too high, as can be inferred from the more accurately measured $B \rightarrow \Lambda_c^{(-)}$ yields [36,34]. Further, the true Λ_c yields in \bar{B} decays is predicted to be reduced significantly from presently accepted values [36,34].

C.2 $\bar{B} \rightarrow DD \bar{K} X$

References [28,38] predicted a sizable wrong charm \bar{D} ($\equiv \bar{D}^0, D^-$) yield in b -decays, which has been confirmed later by CLEO [39,40], ALEPH [41] and DELPHI [42–44]. These processes were left out in the simulations of DELPHI and SLD, thereby introducing a bias in the supposedly totally inclusive B decays.

Once the current $b \rightarrow \bar{D}$ measurements are incorporated, large uncertainties still remain. The $B(b \rightarrow \bar{D})$ is poorly measured at present, and so is the fraction of the time the wrong sign \bar{D} is seen as a D^- versus \bar{D}^0 , which is important for the simulation because of differences in lifetimes and decay patterns. Future studies of $b \rightarrow \bar{D}$ and $b \rightarrow D^{*-}$ will shed light on those issues [36,45].

C.3 $b \rightarrow$ no open charm

The recent flavor specific $b \rightarrow \bar{D}$ measurements made it possible to predict $B(B \rightarrow$ no open charm) in a variety of

ways [20,21]. Either $B(B \rightarrow$ no open charm) is enhanced over conventional estimates and about (10-20)% [46,20], or $B(D^0 \rightarrow K^-\pi^+)$ is sizably below presently accepted values [36,47,48], or both. (If any turns out to be true, current simulations of heavy flavor decays will have to be modified.) Recent studies of DELPHI [44] and CLEO [39] appear not to support a large charmless yield in B decays. In contrast, a new SLD analysis uses all available distinguishing characteristics to determine $B(b \rightarrow sg)$, and is consistent with a significantly enhanced charmless yield [27]. The CLEO analysis suggests a smaller $B(D^0 \rightarrow K^-\pi^+)$ [34].

C.4 $b \rightarrow c\bar{u}d$

About half of all B meson decays are governed by the $b \rightarrow c\bar{u}d$ transitions. Only (10-15)% of the $b \rightarrow c\bar{u}d$ processes have been measured [37]. The rest has to be modeled. The current simulation essentially treats the c and spectator antiquark as one string and the $\bar{u}d$ as another, and fragments the strings independently. We expect to achieve a significant improvement in the simulation if we hadronize the $\bar{u}d$ pair with low invariant mass into resonances as observed in $\tau \rightarrow \nu + \bar{u}d$ decays, and apply HQET methods to the $b \rightarrow c$ transition [21,49]. For $m_{\bar{u}d} > m_\tau$, nonperturbative effects may become important and may be difficult to model. The small color-suppressed amplitude is also harder to model.

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