Eur. Phys. J. C 1, 211–219 (1998)

THE EUROPEAN PHYSICAL JOURNAL C

Large charmless yield in B decays and inclusive B decay puzzles

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Received: 20 December 1996 / Revised version: 15 May 1997

Abstract. In recent studies of inclusive B decays, it has been suggested that either B mesons decay much more copiously to final states with no open charm than currently assumed, or $B(D^0 \to K^-\pi^+)$ has to be reduced significantly. This note takes the experimental $B(D^0 \to K^-\pi^+)$ at its face value and estimates $B(b \to \text{no open charm})$ using complementary methods: one accounts for the c quark in $b \to c$ transitions, the other accounts for the $\bar{c}$ quark in $b \to c\bar{c}s$ transitions. Through cancellation of errors, the average gives our best estimate of $B(b \to \text{no open charm})$, and the difference measures the consistency. The results of the methods are consistent with each other, strongly suggesting a much enhanced $B(b \to \text{no open charm})$. This observation indicates that non-perturbative QCD effects are probably causing a sizable fraction of the $b \to c\bar{c}s$ transitions to be seen as charmless $b \to s$ processes, contrary to smaller traditional expectations. This mechanism has generally been overlooked and may explain the existing experimental data within the framework of the standard model. We then briefly discuss implications on baryon production governed by $b \to c\bar{c}s$ processes, rare hadronic B decays and CP violation studies.

I Introduction

The puzzle of inclusive nonleptonic B decays started out several years ago as the discrepancy between the theoretical prediction and the experimental measurement of the semileptonic branching ratio [1–4]. Theoretical analyses found it difficult to accomodate $B_{s\ell}$ below 0.125 [3], while the experimental value is [5]

$$B_{s\ell} \equiv B(\overline{B} \to X e^- \bar{\nu}) = 0.1049 \pm 0.0046 \,, \tag{1}$$

where $\overline{B}$ represents the weighted average of B^- and $\overline{B}^0$.[1] It was realized that there is a large uncertainty in the theoretical estimate of the $b \to c\bar{c}s$ rate. The rate could increase due to either a small charm quark mass or a failure of local duality [3,4], lowering the prediction for $B_{s\ell}$ down to the experimental value. It would do so, however, at the expense of boosting the charm multiplicity per B decay (n_c) to around 1.3 which is significantly larger than the current experimental value [7]:

$$n_c = 1.10 \pm 0.05 \,. \tag{2}$$

The puzzle was thus rephrased as the inability of theory and experiment to agree simultaneously on $B_{s\ell}$ and n_c [4]. Subsequently, the inclusion of finite charm masses in next-to-leading-order (NLO) calculations was found to enhance the $b \to c\bar{c}s$ rate by about 30% [8–11].

The NLO calculations, however, are not complete (because penguin effects have not yet been included to NLO) and also suffer from large uncertainties due to charm quark mass, renormalization scale and $\alpha_s(M_Z)$. More significantly, the calculation is based on the underlying questionable assumption of local quark-hadron duality. While duality assumes an inclusive rate based on 3-body phase space, the $b \to c\bar{c}s$ transitions proceed sizably as quasi-two body modes, which may enhance the inclusive $b \to c\bar{c}s$ rate considerably [4].

It was then shown [12,13] that the uncertainty in $b \to c\bar{c}s$ can be circumvented by noting that $B_{s\ell}$ and n_c satisfy a linear relation with the theoretical input of[2] [8]

$$r_{ud} \equiv \frac{\Gamma(b \to c\bar{u}d')}{\Gamma(b \to ce\bar{\nu})} = 4.0 \pm 0.4 \,. \tag{3}$$

The above estimate of r_{ud} is based on a complete NLO calculation with finite charm quark mass and non-perturbative corrections up to $\mathcal{O}(1/m_b^2)$. Under the assumption of local duality, the error is dominated by the scale dependence and not by the uncertainties in quark masses and in $\alpha_s(M_Z)$. Combining the accurately measured $B_{s\ell}$ with the predicted r_{ud} and with conventional assumptions regarding charmless yields in inclusive B decays, [13] deduced

$$n_c = 1.30 \pm 0.05, \tag{4}$$
$$B(b \to c\bar{c}s') = 0.32 \pm 0.05 \,. \tag{5}$$

[1] The model-independent extraction of $B(b \to \ell^- X)$ at Z^0 factories overlooked potentially significant effects [6].

[2] Throughout this note, we define $d' \equiv V_{ud}d + V_{us}s$ and $s' \equiv V_{cs}s + V_{cd}d$.

By simple accounting of the then observed 'wrong-charm' yields or by studying the Dalitz plot distribution of the $b \to c\bar{c}s$ transition, a significant 'wrong-charm' $\overline{D}$ production was predicted,

$$B(\overline{B} \to \overline{D}X) \approx 0.2 \,, \tag{6}$$

where $\overline{D}$ represents D^- or $\overline{D}^0$. Subsequently, a sizable wrong charm $\overline{D}$ yield in $\overline{B}$ decays has been observed by both CLEO [14] and ALEPH [15] at approximately half the level as predicted. The observation of the wrong-charm $\overline{D}$'s does not alleviate the charm deficit problem, since the input to the experimental value of n_c is the total inclusive yield of D and $\overline{D}$ combined.

References [6,16] tried to solve the charm deficit problem and related issues by reducing $B(D^0 \to K^-\pi^+)$ sizably below the current world average. However, a recent precise measurement by ALEPH [17], $B(D^0 \to K^-\pi^+) = 0.0390 \pm 0.0009 \pm 0.0012$, agrees with previous measurements. This indicated that inclusive B decays may not be well understood [18,19], and caused us to carefully reassess every input into the puzzle.

In this note, we take full advantage of newly available measurements, in particular the flavor-tagged yields of D, D_s and Λ_c, and systematically identify the source of the charm deficit to be the final states with neither open c nor open $\bar{c}$. This branching fraction is denoted by $B(b \to \text{no open charm})$, and is experimentally well-defined. It is the branching fraction to final states with no weakly decaying charmed hadrons, i.e. those states for which there can be no separate decay vertex resulting from weakly decaying charm. This report then gives a plausible mechanism within the framework of the standard model.

The rest of the paper is structured as follows: In Sect. II, we estimate $B(b \to \text{no open charm})$ in two ways: method A focuses on the c quark in $b \to c$ transitions, and method B focuses on the $\bar{c}$ quark in $W \to \bar{c}s'$ transitions. While method A uses experimental data and involves minimal theoretical input, method B requires a theoretical estimate for r_{ud}. Section III averages over methods A and B (referred to as method C), which reduces errors significantly. Method C gives our best estimate of $B(b \to \text{no open charm})$, while the difference between methods A and B checks the self consistency of the analysis. We find that the experimental data are self consistent and that $B(b \to \text{no open charm})$ is significantly larger than traditional estimates. We then put forward a hypothesis that a sizable component of $c\bar{c}$ pairs are seen as light hadrons and not as open charm [2] through non-perturbative QCD effects. Section IV discusses the systematics of the analysis, which includes correlations among the experimental and theoretical inputs. Conclusions and some implications can be found in the last section.

II Two Ways of estimating $B(b \to \text{no open charm})$

This report distinguishes flavor-specific branching fractions – $B(\overline{B} \to TX)$ and $B(\overline{B} \to \overline{T}X)$ – from the flavor-blind yield per B decay

$$Y_T \equiv B(\overline{B} \to TX) + B(\overline{B} \to \overline{T}X) \,. \tag{7}$$

Table 1. Inclusive charmed hadron production in B meson decays as measured by CLEO

T	$Y_T \equiv B(\overline{B} \to TX) + B(\overline{B} \to \overline{T}X)$	Reference
D	$(0.876 \pm 0.037)\left[\frac{0.0388}{B(D^0 \to K^-\pi^+)}\right]$	[7]
D_s	$(0.1177 \pm 0.0093)\left[\frac{0.036}{B(D_s \to \phi\pi)}\right]$	[21]
Λ_c	$(0.030 \pm 0.005)\left[\frac{0.06}{B(\Lambda_c \to pK^-\pi^+)}\right]$	[41]

The branching fractions quoted by experiments are the average number of particle T per B decay (weighted over charged and neutral B productions). When the particle T is a charmed hadron, however, it is safe to assume that the average number of particle per decay is the same as the branching fraction.

$\overline{B}$ meson decays can be classified as $b \to cl\bar{\nu}(l = e, \mu, \tau)$, $c\bar{u}d'$, $c\bar{c}s'$, $u\bar{c}s'$, and no charm.[3] Then, accounting for the weakly decaying charmed hadrons originating from the c quark in the $b \to c$ transitions, we obtain

$$\begin{aligned} B(b \to \text{no open charm}) &= 1 - B(b \to u\bar{c}s') \\ &- B(\overline{B} \to DX) - B(\overline{B} \to D_s^+X) - B(\overline{B} \to N_cX) \\ &\text{(method A)}, \end{aligned} \tag{8}$$

where

$$\begin{aligned} &B(b \to \text{no open charm}) \\ &\quad \equiv B(b \to \text{no charm}) + B(\overline{B} \to (c\bar{c})X) \end{aligned} \tag{9}$$

with $(c\bar{c})$ being charmonia not seen as $D\overline{D}X$, and N_c denotes any of the weakly decaying charmed baryons (namely, Λ_c, Ξ_c or Ω_c). The branching fraction $B(b \to u\bar{c}s')$ is small, and estimated to be

$$B(b \to u\bar{c}s') = \left|\frac{V_{ub}}{V_{cb}}\right|^2 \eta\, r_{ud}\, B(b \to ce\bar{\nu}) = 0.0035 \pm 0.0018 \,,$$

where $\eta \approx 1.3$ accounts for the larger QCD corrections in $W \to \bar{c}s'$ transitions [9–11] with respect to those in $W \to \bar{u}d'$ [8]. Aside from this tiny correction, Method A involves essentially no theoretical input.

The experimental inputs used in (8) are given in Tables 1–3. Table 1 shows the flavor-blind number of each particle type per B decay (Y_T) and Table 3 shows the flavor-specific content of each yield. Together, they provide flavor-specific branching fractions needed in (8). We have used consistent values for the key branching fractions of charm decays. The updated values are summarized in Table 2. The experimental value of $B(D^0 \to K^-\pi^+)$ is

[3] 'No charm' indicates that there is no c nor $\bar{c}$ quark in the final state at quark level and includes $b \to ul\bar{\nu}$, $u\bar{u}d'$, and charmless $b \to s'$ transitions.

Table 2. Absolute branching ratios of key charm decays as used in this note

Quantity	Value	Comment
$B(D^0 \to K^-\pi^+)$	0.0388 ± 0.0010	World Average [20]
$r_+ \equiv \frac{B(D^+\to K^-\pi^+\pi^+)}{B(D^0\to K^-\pi^+)}$	2.35 ± 0.23	CLEO [47]
$r_s \equiv \frac{B(D_s\to\phi\pi)}{B(D^0\to K^-\pi^+)}$	0.92 ± 0.23	CLEO [48]
$B(\Lambda_c \to pK^-\pi^+)$	0.060 ± 0.015	CLEO [46], see Appendix

Table 3. Inclusive charmed hadron production in tagged B decays as measured by CLEO

Observable	Value	Reference
$r_{\Lambda_c} \equiv \frac{B(\overline{B}\to\overline{\Lambda}_cX)}{B(\overline{B}\to\Lambda_cX)}$	0.20 ± 0.14	[41]
$r_D \equiv \frac{B(\overline{B}\to\overline{D}X)}{B(\overline{B}\to DX)}$	0.107 ± 0.034	[14]
$f_{D_s} \equiv \frac{B(\overline{B}\to D_s^+X)}{Y_{D_s}}$	0.172 ± 0.083	[21]

taken to be the new world average after the Warsaw '96 Conference [20]:

$$B(D^0 \to K^-\pi^+) = 0.0388 \pm 0.0010\,. \tag{10}$$

Both $B(D^+ \to K^-\pi^+\pi^+)$ and $B(D_s^+ \to \phi\pi^+)$ are measured model-independently and are proportional to $B(D^0 \to K^-\pi^+)$. The measured ratios are given in Table 2.

Using the values in Tables 1–3 and the definition

$$r_D \equiv \frac{B(\overline{B} \to \overline{D}X)}{B(\overline{B} \to DX)}\,, \tag{11}$$

the flavor-specific 'wrong-sign' $\overline{D}$ ($\overline{D}^0$ or D^-) yield is

$$B(\overline{B} \to \overline{D}X) = Y_D \times \frac{r_D}{1+r_D} = 0.085 \pm 0.025 \quad \text{(CLEO)}\,. \tag{12}$$

The same quantity can be inferred from the ALEPH measurement of $\overline{B} \to D\overline{D}X$ [15] to be (see Appendix)

$$B(\overline{B} \to \overline{D}X) = 0.145 \pm 0.037 \quad \text{(ALEPH)}\,. \tag{13}$$

The CLEO and ALEPH results are consistent with each other within two standard deviations. The agreement is mildly encouraging since they have been measured using completely different methods. The 'right-sign' D yield as well as the flavor-specific yields of D_s and Λ_c are obtained similarly to (12). The flavor-specific D_s^+ production in $\overline{B}$ decays has been measured to be small by CLEO [21] (see Table 3). This conclusion has been confirmed by ALEPH [15].

The most accurate measurements regarding charmed baryon production in B decays involve Λ_c baryons. In contrast, Ξ_c production in B decays involves large experimental uncertainties, and the Ω_c yield has not yet been observed. Instead of the uncertain and nonexistent measurements, [6,16] inferred the inclusive N_c yields by correlating them to the more accurately measured Λ_c yields (see Appendix). It predicted the Ξ_c production to be drastically reduced with regard to the measured central value [22]. The drastic reduction can be traced back to a large enhancement in the absolute BR scale of Ξ_c decays, a conclusion supported by recent work of Voloshin [23].

We now turn to the second way (method B) of estimating $B(b \to \text{no open charm})$ which is to account for the $\bar{c}$ quark in $b \to c\bar{c}s'$, $u\bar{c}s'$ transitions. Noting that, apart from charmonia, the $\bar{c}$ quark hadronizes to $\overline{D}$, D_s^-, or $\overline{N}_c$, we obtain

$$\begin{aligned} &B(b \to \text{no open charm}) \\ &\quad = R - B(\overline{B} \to \overline{D}X) - B(\overline{B} \to D_s^-X) \\ &\quad\quad - B(\overline{B} \to \overline{N}_cX) \\ &\quad\quad\quad \text{(method B)}\,. \end{aligned} \tag{14}$$

Here R is the 'remainder' of $\overline{B}$ branching fractions after reliable components have been subtracted:

$$\begin{aligned} R &\equiv B(b \to \text{no charm}) + B(b \to c\bar{c}s') + B(b \to u\bar{c}s') \\ &= 1 - B(b \to c(e,\mu,\tau)\overline{\nu}) - B(b \to c\bar{u}d') \\ &= 1 - B(b \to ce\overline{\nu})\,(2 + r_\tau + r_{ud})\,. \end{aligned} \tag{15}$$

The normalized tau semileptonic rate

$$r_\tau \equiv \frac{\Gamma(b \to c\tau\overline{\nu})}{\Gamma(b \to ce\overline{\nu})} = 0.22 \pm 0.02 \tag{16}$$

is reliably estimated by theory [24], and is consistent with present measurements. Using this as well as (1) and (3), one finds $R = 0.35 \pm 0.05$. This result changes only minimally to

$$R = 0.36 \pm 0.05\,, \tag{17}$$

when Pauli interference and W annihilation effects are taken conservatively into account [25,26]. Our prediction (17) for R combines the most accurate information available from both theory and experiment.

Using the experimental values from Tables 1–3, we obtain for methods A and B,

$$\begin{aligned} &B(b \to \text{no open charm}) = \\ &\quad 0.15 \pm 0.05\ \text{(A)}\,,\ 0.17 \pm 0.06\ \text{(B)} \quad \text{(CLEO)} \quad (18) \\ &\quad 0.21 \pm 0.06\ \text{(A)}\,,\ 0.11 \pm 0.07\ \text{(B)} \\ &\quad\quad \text{(ALEPH\&CLEO)}\,. \quad (19) \end{aligned}$$

In (19), we have used $B(\overline{B} \to \overline{D}X)$ given by (13) and

$$B(\overline{B} \to DX) = Y_D - B(\overline{B} \to \overline{D}X)$$

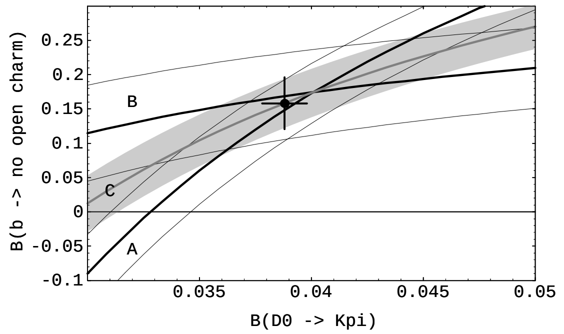

Fig. 1. Methods (labeled A, B, C; see text for detail) of estimating $B(b \to \text{no open charm})$ are plotted against $B(D^0 \to K^-\pi^+)$ together with bands corresponding to one standard deviation using CLEO data. The point with error bars shows the world average of $B(D^0 \to K^-\pi^+)$ and the best estimate of $B(b \to \text{no open charm})$ via method C

with all other inputs (including Y_D) being identical to those of (18).

Figure 1 shows the estimates of $B(b \to \text{no open charm})$ as functions of $B(D^0 \to K^-\pi^+)$ using CLEO data only. The experimental value of $B(D^0 \to K^-\pi^+)$ is well within the overlap of the two bands, which represent methods A and B. This indicates self consistency of the inputs.

III Best estimate for $B(b \to \text{no open charm})$ and interpretations

The errors in methods A and B are highly correlated. For example, when the ratio of wrong-sign to right-sign D's (r_D) fluctuates upward, the value given by A will increase while that given by B will decrease. The best estimate of $B(b \to \text{no open charm})$ can be obtained by averaging over methods A and B, where the errors due to flavor-specific fractions (namely, r_D, r_{Λ_c} and f_{D_s}; see Table 3) cancel:

$$\begin{aligned} B(b \to \text{no open charm}) &= 0.5\ (1 + R - B(b \to u\bar{c}s') \\ &\quad - Y_D - Y_{D_s} - Y_{N_c}) \\ &\quad \text{(method C)} \\ &= 0.16 \pm 0.04 \quad \text{(CLEO)}. \end{aligned} \tag{20}$$

The correlations are properly taken into account in the error estimation. The value is much larger than the traditional estimate of $B(b \to \text{no open charm})$.

Equation (9) defines $B(b \to \text{no open charm})$, where

$$B(b \to \text{no charm}) = B(b \to u(\text{no } \bar{c})) + B(b \to s') \ . \tag{21}$$

Here $B(b \to s')$ includes $b \to s'(ng, q\bar{q})$ processes and interference effects.

The $b \to u$ transitions are not large ($\sim 1\%$) because of the small value of $|V_{ub}/V_{cb}|$, while the $b \to s'$ transitions have been argued to be small due to the small Wilson coefficients of penguin operators [27]. Traditional estimates yield [13]

$$B(b \to \text{no charm}) = 0.026 \pm 0.010 \quad \text{(traditional guess)}. \tag{22}$$

Conventional charmonia ($c\bar{c}$) production in B decays has been estimated to be [13]

$$B(\overline{B} \to (c\bar{c})X) = 0.026 \pm 0.004 \quad \text{(traditional guess)}. \tag{23}$$

It used experimental measurements for $J/\psi, \psi', \chi_{c1}$, and χ_{c2} together with theoretical estimates of other hidden charmonia not yet detected. The $B(B \to \eta_c X, \eta_c' X)$ predictions used published calculations for decay constants of η_c, η_c' and related their yields to that of J/ψ assuming color-suppressed factorization, which cannot be justified theoretically [28]. The total yield of other charmonia including those not expected from factorization (such as h_c and χ_{c0}) were assumed to be $1.2B(B \to \chi_{c2}X)$.[4] Adding up (22) and (23), we obtain

$$B(b \to \text{no open charm}) = 0.052 \pm 0.011 \quad \text{(traditional guess)}. \tag{24}$$

The traditional estimate (24) falls far below 0.16 ± 0.04. Though estimate (23) is unreliable due to the questionable assumptions made, we do not expect the true conventional ($c\bar{c}$) production to be large enough to explain the bulk of the discrepancy. What could be the source of such a large enhancement of $B(b \to \text{no open charm})$?

New physics is one possible solution [18]. But before drawing that conclusion, all standard model explanations, including non-perturbative effects, have to be ruled out. We hypothesize that non-perturbative effects could cause a significant fraction of $c\bar{c}$ pairs produced in B decays to be seen as light hadrons [2]. This hypothesis does not modify the previous analysis since the expressions for methods A and B [(8) and (14)] allow for $c\bar{c}$ transformations to light hadrons and only assume that singly produced charm decays weakly.

How realistic is such a scenario? The QCD corrected operator responsible for the $b \to c\bar{c}s$ transition can be written as (neglecting the small conventional penguin contributions)

$$2c_2(\bar{s}T^a b)_{V-A}(\bar{c}T^a c)_{V-A} + \left(c_1 + \frac{c_2}{N_c}\right)(\bar{s}b)_{V-A}(\bar{c}c)_{V-A} \ . \tag{25}$$

The estimate for the coefficient of the color-singlet term $(c_1 + c_2/N_c)$ ranges from 0.10 to 0.25 and is much smaller than $c_2 \approx 1.1$ [28]. Thus, the $c\bar{c}$ quark pair is produced dominantly in a color-octet configuration. This means that the $c\bar{c}$ pair can annihilate into a single gluon. Such effects, however, have already been included in the short-distance, perturbative calculations of $b \to s'$. Whatever may enhance the $c\bar{c}$ transformation into light hadrons should then be due to non-perturbative effects.

One possibility is that light hadrons have a non-negligible $c\bar{c}$ component [29,30]. The part of the light hadron $[\pi, \rho, K^{(*)}$, etc.$]$ wavefunction that involves intrinsic charm will have maximal amplitude at minimal off-shellness and minimal invariant mass [29]. Thus it maybe significant

[4] Equation (23) is clearly unreliable and one should search for not only η_c in B decays [22] but also for other ($c\bar{c}$), such as $\eta_c', \chi_{c0}, h_c, {}^1D_2, {}^3D_2$.

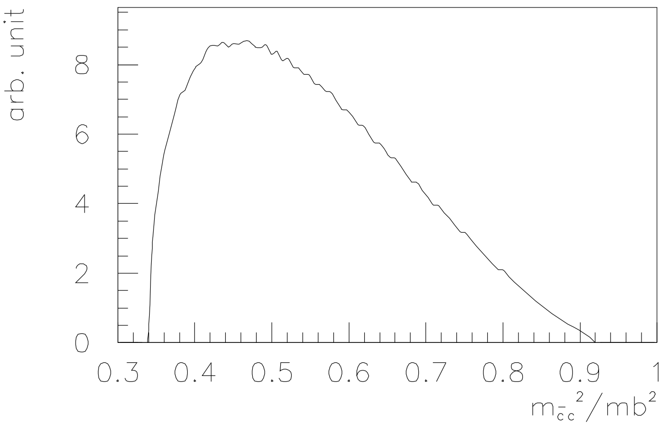

Fig. 2. The invariant mass distribution of the $c\bar{c}$ pair in the decay $b \to c\bar{c}s$ [13]

that the $c\bar{c}$ pairs produced in $b \to c\bar{c}s$ transitions favor low invariant masses (see Fig. 2).

Another candidate is a sizable production of $c\bar{c}g$ hybrids (denoted as H_c) [31–35] where the $c\bar{c}$ pair is expected to be predominantly in a color-octet state.[5] Such hybrid states may couple strongly to the color-octet $c\bar{c}$ pair produced in $\overline{B}$ decays governed by $b \to c\bar{c}s'$ transitions. The masses of the lowest lying $c\bar{c}$-hybrid mesons are predicted to be above open charm threshold [31,34,35]. Still, their widths are expected to be narrow because of selection rules that suppress the $H_c \to D^{(*)}\overline{D}^{(*)}$ transitions [32,36]. The $H_c \to D\overline{D}^{**}, D^{**}\overline{D}$ processes are kinematically forbidden, except for the reduced production of the broad D^{**} mesons with low invariant masses. Thus, such hybrid mesons may be seen significantly as light hadrons. At present, there is no firm proof that this mechanism can account for the observed enhancement of $B(b \to$ no open charm). Non-perturbative QCD effects, however, are rich and poorly known. We thus consider it important to investigate further theoretically and experimentally whether a significant portion of $c\bar{c}$ pairs produced in $\overline{B}$ decays could be seen as light hadrons.

IV Systematics and correlations among observables

The self consistency of inputs can be checked by taking the difference of the two methods which should equal zero:

$$B(b \to \text{no open charm})\ (\text{A}) - B(b \to \text{no open charm})\ (\text{B})$$
$$= -0.02 \pm 0.08 \qquad (\text{CLEO}) \tag{26}$$
$$0.10 \pm 0.10 \qquad (\text{ALEPH\&CLEO}). \tag{27}$$

The CLEO data are clearly self consistent, but the ALEPH data also are not inconsistent.

Equivalently, equating methods A and B, we obtain a relation among input parameters $B(D^0 \to K^-\pi^+)$, r_D, Y_T, r_{ud}, etc. among which r_{ud} is the only significant theoretical input (other theoretical parameters are either reliable or small). This relation can be used to check the self consistency of the inputs, or to solve for one of the parameters in terms of all else. Solving for $B(D^0 \to K^-\pi^+)$, r_D, and r_{ud}, one obtains (using CLEO data only)

$$B(D^0 \to K^-\pi^+) = 4.0 \pm 0.5\%\ , \tag{28}$$
$$r_D = 0.12 \pm 0.05\ , \tag{29}$$
$$r_{ud} = 4.1 \pm 0.7\ . \tag{30}$$

Note that the above determination of r_{ud} uses experimental inputs only. The fact that these values are consistent with the input values themselves indicates that the inputs are self consistent. We will first discuss the systematics of each input, and then examine the correlations among them.

IV.1 $\mathbf{Y_D}$ and $\mathbf{Y_{D_s}}$

Could CLEO have badly mismeasured the coefficient (0.876 ± 0.037) of Y_D and/or the coefficient (0.1177 ± 0.0093) of Y_{D_s} (i.e., apart from $B(D^0 \to K^-\pi^+)$, see Table 1)? In order for the best estimate of $B(b \to$ no open charm) (method C) to come down to the 5% level, $Y_D + Y_{D_s}$ needs to increase by about 20%. That appears unlikely since then the charm multiplicity in B decays as measured by CLEO should be significantly different from recent ALEPH [37] and OPAL [38] measurements which are given in Table 4. Such a comparison is justified since the combined yields of D, D_s, Λ_c in b-hadron decays at Z^0 and $\Upsilon(4S)$ factories are expected to agree within existing experimental errors. Table 4 shows the consistency of the measurements. Also, method A is more sensitive to the change in Y_D and Y_{D_s} than method B, and increasing Y_D and Y_{D_s} by 20% results in a 2-sigma discrepancy between the two methods evaluated at the nominal value of $B(D^0 \to K^-\pi^+)$.

IV.2 Charmed baryon yield

We decided not to use the experimental Ξ_c data, and adopted a model prediction which gave branching fractions smaller than the experimental values. Even if we were to double the total charmed baryon yield in B meson decays, however, the result $B(b \to$ no open charm$) = 0.14 \pm 0.04$ via method C would still be significantly larger than the traditional estimate. Thus, our conclusion is not sensitive to the uncertainty in the charmed baryon yield.

IV.3 Wrong-sign/right-sign ratio of D meson ($\mathbf{r_D}$)

The wrong-sign/right-sign ratio of D mesons, r_D, still has large uncertainties. The method currently employed by CLEO uses angular correlations between a high energy

[5] We are grateful to J. Kuti for pointing this out to us.

Table 4. Charm multiplicity in B meson decays at $\Upsilon(4S)$, $Y_T \equiv B(\overline{B} \to TX) + B(\overline{B} \to \overline{T}X)$, and in b-hadron decays at $Z^0, Y_T \equiv B(b \to TX) + B(b \to \overline{T}X)$

Quantity	CLEO [7]	ALEPH [37]	OPAL [38]
$(Y_D + Y_{D_s})\frac{B(D^0\to K^-\pi^+)}{0.0388}$	0.99 ± 0.04	1.01 ± 0.05	0.93 ± 0.06
$Y_{\Lambda_c}\frac{B(\Lambda_c\to pK^-\pi^+)}{0.06}$	0.030 ± 0.005	0.08 ± 0.01	0.09 ± 0.02
$Y_D + Y_{D_s} + Y_{\Lambda_c}$	1.02 ± 0.05	1.09 ± 0.07	1.02 ± 0.08

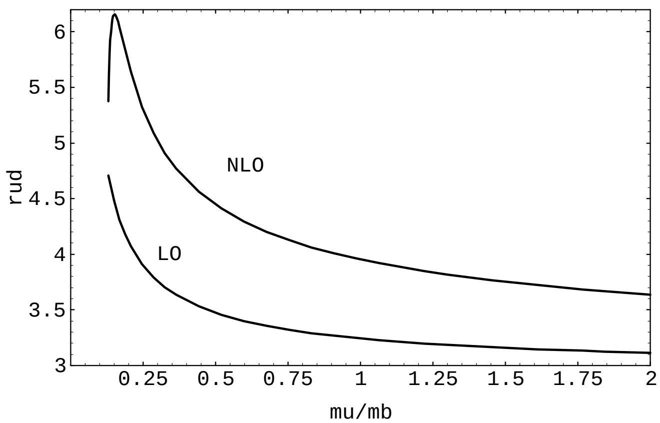

Fig. 3. Scale dependence of the $b \to c\bar{u}d'$ rate normalized to the semileptonic rate (r_{ud}) for the leading-order (LO) and the next-to-leading-order (NLO) approximations [8]

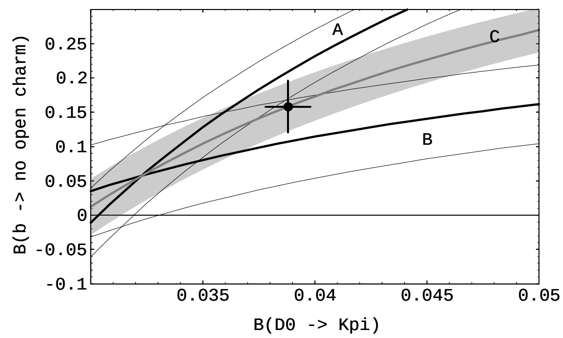

Fig. 4. Same as Fig. 1, except for the value of r_D which is hypothetically taken to be 0.20 ± 0.03

lepton and a D meson to separate the cases where the D-lepton pair comes from the same $\overline{B}$ meson or different $\overline{B}$ mesons. At low D momenta, however, the angular correlation is smeared out and it is difficult to distinguish the two cases. The ALEPH measurement fully reconstructs both charmed mesons from a single B thus avoiding such systematics, but suffers from low statistics. Z^0 factories should be able to determine r_D more accurately by measuring the inclusive yield of single D's in b-enriched data samples that are optimally flavor-tagged. Neither flavor-tagging nor $B^0 - \overline{B}^0$ mixing corrections would be necessary, if a large charged B sample could be isolated.

IV.4 $\mathbf{r_{ud}}$

Another possibility is that theory is unable to predict r_{ud} reliably. Local quark-hadron duality may not hold. Once local duality is assumed, the most important uncertainty lies in the choice of scale μ, as mentioned earlier [8]. Figure 3 demonstrates a troubling aspect of the calculation. Contrary to expectation, there is no significant reduction in sensitivity on μ when going from leading-order to next-to-leading order. Maybe r_{ud} has a significantly larger uncertainty than currently appreciated. It is gratifying to note that the recent measurements of wrong charm yields allow the experimental determination of r_{ud}, which agrees with theory.

If the theoretical estimate of r_{ud} is not to be trusted, one has to rely on method A which does not depend on r_{ud}. Note that the averaging used in method C reduces the sensitivity to the uncertainty in r_{ud}.

IV.5 Correlation between $\mathbf{r_D}$ and $\mathbf{B(D^0 \to K^-\pi^+)}$

Figure 4 shows the hypothetical case of $r_D = 0.20 \pm 0.03$, which agrees with the central value of the ALEPH measurement [(13)]. The lines would cross at $B(b \to$ no open charm$) = 0.06$ and $B(D^0 \to K^-\pi^+) = 0.032$. It demonstrates that increasing the wrong charm yield makes $B(b \to$ no open charm) more consistent with the traditional estimate. The charm deficit would disappear due to the lower value of $B(D^0 \to K^-\pi^+)$. Thus if r_D is measured to be around 0.2 with good accuracy, then one suspect would be a mismeasured $B(D^0 \to K^-\pi^+)$. A more plausible culprit, however, would be a smaller r_{ud} than theoretically predicted, as discussed next.

IV.6 $\mathbf{B(b \to}$ no open charm) and $\mathbf{r_{ud}}$ vs $\mathbf{r_D}$

Figure 5 shows r_D dependences of r_{ud} and $B(b \to$ no open charm) (method A) both of which use experimental inputs only. If r_D were small and around 0.05, one sees that $B(b \to$ no open charm) is $\sim 0.11 \pm 0.05$ which is within 1 sigma of the traditional estimate, and $r_{ud} \sim 4.9 \pm 0.6$. The value of $r_{ud} \sim 5$ corresponds to $\mu \sim m_b/3$.[6] This set of parameters would be more or less consistent with the standard model without invoking new physics nor enhanced $c\bar{c}$ transformation into light hadrons. If on the other hand we

[6] Using the BLM scale-setting method [39], it has been estimated that such small scales could be appropriate [40].

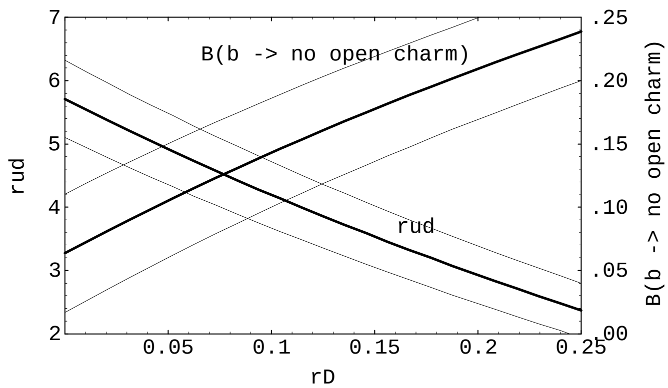

Fig. 5. $B(b \to \text{no open charm})$ (method A) and r_{ud} as functions of r_D. The inputs are essentially experimental only

take $r_D = 0.20 \pm 0.03$, one obtains $r_{ud} = 2.9 \pm 0.6$, which disfavors small renormalization scales. These discussions clearly show the importance of accurate measurements of r_D.

V Summary and discussion

Newly available flavor-tagged data made it possible to apply complementary methods to estimate $B(b \to \text{no open charm})$. Comparisons of the methods allowed us to study correlations and self consistency of inputs. $B(b \to \text{no open charm})$ has been found to be much larger than generally accepted. The observation may indicate that non-perturbative effects cause an appreciable fraction of produced $\bar{c}c$ pairs in B decays to be seen as light hadrons.

A large $B(b \to \text{no open charm})$ could well be the final missing piece in the puzzle of the small charm multiplicity in B decays and small $B(\overline{B} \to X \ell \overline{\nu})$. The proposed mechanism of annihilation of $\bar{c}c$ pairs could explain the low observed ratio of[41]

$$B(\overline{B} \to \overline{N}_c X)/B(\overline{B} \to N_c X).$$

The numerator is governed essentially by $b \to c\bar{c}s'$ transitions, where a sizable fraction of $c\bar{c}$ pairs may not be seen as open charm thereby reducing the charmed baryon yield. In contrast, the denominator is dominated by $b \to c\bar{u}d'$ processes which would result in single open charm. The mechanism of $c\bar{c}$ transformation is also consistent with the observed significant surplus of K^- in inclusive $\overline{B}$ decays beyond conventional sources and the measured large K-flavor correlation with B-flavor at time of decay [42, 22].

One way to measure $B(b \to \text{no open charm})$ could use a vertex detector which searches in a b-enriched sample for a b-decay vertex and vetoes on additional vertices from open charm. In addition, one could then search for a kaon attached to the vertex.

If our predictions are confirmed, then many studies of rare B decays and CP violation will have to be re-evaluated. Through non-perturbative effects, amplitudes governed by $b \to d$ (s) transitions could have enhanced contributions governed by the combination of CKM matrix elements $V_{cb}V_{cd}^*$ $(V_{cb}V_{cs}^*)$. This indicates that the rate of $\overline{B} \to K^-\pi^+$ would be larger than that of $\overline{B} \to \pi^-\pi^+$ which is consistent with a recent observation [43]. Further, the penguin amplitude in $b \to d$ processes may be enhanced such that direct CP violation may become observable either inclusively or exclusively, as in $B \to \pi\rho, \pi\omega, \pi a_1$, $3\pi, B^0 \to \pi^+\pi^-$. Also, the recently observed large value of $B(B^- \to \eta' K^-)$ [43,44] and $B(B^- \to \eta' X; P_{\eta'} > 2.2$ GeV/c) [43] may be relevant in this context. Many CP studies with such rare decay modes and similar ones will have to be rethought.

Estimates of non-perturbative QCD effects are important to reliably compute the $B_s - \overline{B}_s$ width difference [26] and the inclusive, mixing-induced CP violating effects in B_d decays governed by $b \to u\bar{u}d, c\bar{c}d$ transitions [45]. Superb vertex detectors would still be able to isolate the inclusive $b \to u\bar{u}d$ transitions but the signal of singly detached vertices may involve a larger background than previously appreciated.

Acknowledgements. It is a pleasure to thank P. Ball, M. Beneke, G. Buchalla, F.E. Close, A. Falk, A. Kagan, J. Kuti, C. Morningstar, P. Page and H. Quinn for discussions, and T. Browder and G. Buchalla for comments on an earlier draft. Many thanks go to Lois Deringer who diligently typed up this manuscript. This work was supported in part by the Department of Energy, Contract No. DE-AC02-76CH03000 and Grant No. DE-FG02-91ER40654.

Appendix

The ALEPH measurement of $\overline{B} \to D\overline{D}X$[15] is

$$B(\overline{B} \to D^0\overline{D}^0X, D^0D^-X, D^+\overline{D}^0X) = 0.128 \pm 0.027 \pm 0.026\ . \quad \text{(A.1)}$$

In order to obtain $B(\overline{B} \to \overline{D}X)$, we need to add $B(\overline{B} \to D^+D^-X)$ and $B(\overline{B} \to D_s^+\overline{D}X)$ ($\overline{B} \to N_c\ \overline{N}\ \overline{D}X_s$ is kinematically forbidden and $\overline{B} \to N_c\ \overline{N}\ \overline{D}X$ is negligible). The total D^+D^-X production can be evaluated from ALEPH's measurements [15] by assuming factorization and isopin symmetry[6] to be $1 \pm 0.4\%$, where we have assigned a conservative error since the assumption of factorization may not hold.

Our estimate for D_s^+ production in $b \to c\bar{c}s$ processes is small. In fact, the measured total D_s^+ production in tagged $\overline{B}$ decays is $Y_{D_s}f_{D_s} = 2 \pm 1\%$ (Tables 1–3), which informs about the probability $P(b \to c \to D_s^+)$. Since about 10% of all $\overline{B}$'s decay as $b \to c + \overline{D}X_s$, and the formation of D_s^+ from the c quark entails phase-space suppression [due to the existence of the two charmed mesons and two extra strange quarks in the final state], we estimate that $B(\overline{B} \to D_s^+\overline{D}X)$ not to exceed significantly the permille level. Correcting for the key charm decay branching fractions adopted in this note, we then obtain (13).

Table 5. Charmed baryon $[N_c \equiv \Lambda_c, \Xi_c, \Omega_c]$ production in B meson decay as predicted in [6,16]

Quantity	Value
$B(\overline{B} \to N_c X)$	$(0.0365 \pm 0.0065) \left[\frac{0.06}{B(\Lambda_c \to pK^-\pi^+)}\right]$
$B(\overline{B} \to \overline{N}_c X)$	$(0.0059 \pm 0.0038) \left[\frac{0.06}{B(\Lambda_c \to pK^-\pi^+)}\right]$
Y_{N_c}	$(0.0424 \pm 0.0082) \left[\frac{0.06}{B(\Lambda_c \to pK^-\pi^+)}\right]$

$B(\overset{(-)}{B} \to N_c X)$ can be related to the measurements on Λ_c using a model [6,16]. The assumptions of the model are: (1) in charmed baryon production governed by the $b \to c\overline{q}q'$ transition, the two quarks cq' end up in a single (excited) charmed baryon, (2) excited Ξ_c will end up as Ξ_c and excited Λ_c (or Σ_c) will end up as Λ_c, and (3) the ratio of $s\overline{s}$ pair creation to $u\overline{u}$ or $d\overline{d}$ pair creation is universal. The estimate for $B(\overset{(-)}{B} \to N_c X)$ is listed in Table 5. The predicted Ξ_c production is found to be much smaller than the measurement, and when any of the assumptions are relaxed toward more realistic ones, the prediction becomes even smaller. Following the ideology presented in [6,16], the results of the model can be interpreted therefore as model-independent upper limits on strange charm baryon yields in B decays.

There exists another minor modification. References [6,16] claim that one must reassess the currently accepted value of $B(\Lambda_c \to pK^-\pi^+) = 0.044 \pm 0.006$ because it has been based on a flawed model for $\overline{B} \to N_c X$. The model is invalidated if sizable $\overline{B} \to D^{(*)} \overset{(-)}{N} X$ are observed, which were predicted from simple Dalitz plot arguments. References [6,16] thus argue to use [46]

$$B(\Lambda_c \to pK^-\pi^+) = 0.060 \pm 0.015 , \qquad (A.2)$$

a value adopted throughout this note.

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