Enhanced Charmless Yield in $B$ Decays and Inclusive $B$-Decay Puzzles

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Our analysis suggests that the charmless yield in $B$ decays is enhanced over traditional estimates. The $c\bar{c}$ pair produced in $b\rightarrow c\bar{c}s$ transitions may be seen significantly as light hadrons due to non-perturbative effects. Existing data samples at $\Upsilon(4S)$ and $Z^0$ factories allow key measurements which are outlined.

1 Motivation

One prime motivation for optimizing our understanding of inclusive $B$ decays is CP violation. CP asymmetries at the 50% level are predicted for the time-evolved $B_d \rightarrow J/\psi K_S$ decays, within the CKM model. The few hundred reconstructed $J/\psi K_S$ events would thus allow meaningful CP studies, once they are tagged. Tagging denotes distinction of an initially pure $B_d$ and $\bar{B}_d$. An optimal tagging algorithm combines self-tagging and with all available information from the other $b$-hadron decay. Thus inclusive $b$-hadron decays must be understood. Such an understanding would enhance CP studies with $B$ samples both inclusive or exclusive. It would reduce backgrounds for any $B$-decay under study. Intriguing hadronization effects may be discovered.

2 Traditional Puzzles

The $b$ is known to decay normally to a $c$, and that charm flavor is referred to as “right” charm. In contrast, the $b \rightarrow \bar{c}$ process produces “wrong” charm. The penguin amplitudes give rise to $b \rightarrow s$ transitions, which are seen as a kaon, additional light hadrons, and possibly additional $K\bar{K}$ pairs. Due to the small $|V_{ub}/V_{cb}| \sim 0.1$, the $b \rightarrow u$ transitions are negligible at the present level of accuracy. Theory calculates the rates for $b \rightarrow c\ell\nu$, $b \rightarrow c\bar{s}$, and the ratio of rates

$$r_{ud} \equiv \frac{\Gamma(b \rightarrow c\bar{s}\ell\nu)}{\Gamma(b \rightarrow c\bar{u}\ell\nu)} = 4.0 \pm 0.4.$$  \hspace{1cm} (1)

The CKM parameters cancel in the ratio. The phase-space factor cancels in leading order and $r_{ud}$ would be 3 because of color counting. QCD corrections (complete to next-to-leading-order with finite charm quark mass) have been found to enhance this ratio to $4.0\pm0.4$. Of course we are not dealing with freely
decaying $b$-quarks, but with decays of $b$-hadrons. It must thus be emphasized that the calculation of $r_{ud}$ assumes local quark-hadron duality.

In this talk, $b$ denotes the weighted average of produced $B$ mesons. The semileptonic BR is

$$BR_{s\ell} \equiv \frac{\Gamma(b \to Xe^{-}\nu)}{\Gamma(b \to \text{all})},$$

and the charm multiplicity $(-c)_{b}$ per $b$ decay is given by

$$n_{c} = \frac{\#(-c)}{\#b} = 1 - B(b \to \text{no charm}) + B(b \to c\bar{c}s').$$

The current theoretical status is summarized in Fig. 1, which plots the theoretically allowed $(n_{c}, BR_{s\ell})$ region.

The low (high) horizontal curve is for a large (small) $m_{c}/m_{b}$ ratio. The diagonal curves are given for various renormalization scales. The left boundary is given by $\mu/m_{b} = 0.25$, for which $r_{ud} \gtrsim 5$, see Figure 2.

Figure 1: Theoretical prediction for the semileptonic branching ratio and charm multiplicity. The data points show the average experimental values obtained at $\Upsilon(4S)$ (LE) and $Z^{0}$ (HE) factories. Figure taken from Ref. 12.
The measured charm multiplicity per $B$ decay $n_c$ (as summarized in Fig. 1) must be revised downward significantly, because of several reasons. First, the measured central value of $\Xi_c$ production is too large. An upper-limit has been derived and is drastically smaller. The drastic reduction can be traced back to a large enhancement in the absolute BR scale of $\Xi_c$ decays, a conclusion supported by recent work of Voloshin. Second, the world-average for $B(\Lambda_c \to pK^-\pi^+) = 0.044 \pm 0.006$ must be sizably revised upward to $0.08 \pm 0.02$. This causes $n_c$ to decrease more significantly at $Z^0$-factories (because of $\Lambda_b$ production) than at $\Upsilon(4S)$ factories.

However, $n_c$ and $BR_{s\ell}$ are not the only observables. With the recent flavor specific measurement of wrong-sign $D$ ($D^0$ or $D^-$) production in $b$ decay, $B(b \to D)$, the quantity $r_{ud}$ can now be experimentally extracted,

$$r_{ud}[\text{exp.}] = \frac{B(b \to \text{open } c) - B(b \to \text{open } \bar{c}) + B(b \to u\bar{c}s')}{BR_{s\ell}} - 2 - r_{\tau}, \quad (5)$$
with minimal theoretical input, including

\[ B(b \rightarrow u\bar{c}s') = 0.0035 \pm 0.0018, \text{ and} \]

\[ r_\tau = 0.22 \pm 0.02. \]  

Using CLEO data alone \( r_{ud}[\exp.] = 4.1 \pm 0.7 \) \( [17] \).

The sizable \( b \rightarrow D \) observation unearthed an overlooked background \( b \rightarrow D \rightarrow \ell^- \) in model-independent, inclusive \( BR_{st} \) measurement \( [14] \). The \( Z^0 \) measurement will be reduced significantly, and is more affected than the \( \Upsilon(4S) \) measurements because of differences in cuts on the signal lepton momentum. The model-independent extraction of \( BR_{st} \) requires the removal of \( B^0 - \overline{B}^0 \) mixing effects and the value of the average mixing parameter \( \chi \) as input. But both the value of \( \chi \) and the removal of \( B^0 - \overline{B}^0 \) mixing effects will have to be modified, because the secondary leptons \( b \rightarrow c \rightarrow \ell \) experience different mixing than the primary leptons \( b \rightarrow \ell^- \) \( [14] \). We anticipate \( [14] \) that reanalyses of data will significantly reduce the difference between the \( BR_{st} \) measurements from the \( Z^0 \) and \( \Upsilon(4S) \) environments in favor of the lower \( \Upsilon(4S) \) result \( [22] \).

After applying the revisions onto Fig. 1, the experimental measurements from \( \Upsilon(4S) \) and \( Z^0 \) factories are consistent. The \( \Upsilon(4S) \) data support a low renormalization scale \( \mu \), and are marginally consistent with theory based on the heavy quark expansion \( [13,12] \).

### 3 Flavor-Specific Input

CLEO \( [19] \) and ALEPH \( [20] \) determined

\[ B(b \rightarrow D) = \begin{cases} 
0.085 \pm 0.025 & \text{CLEO 1996} \\
0.145 \pm 0.037 & \text{ALEPH 1996} 
\end{cases} \]  

Do those measurements confirm the prediction \( [3] \) of \( B(b \rightarrow D) \sim 0.2 \)?

To answer that question, a synthesis of all available data, flavor-specific and flavor-blind, was in order. The \( B(b \rightarrow \text{no open charm}) \) is that fraction of \( D \) decays which has no weakly decaying charm, that is, no separate charm vertex. It can be inferred indirectly \( [3] \).

Method A:

\[ B(b \rightarrow \text{no open charm}) = 1 - B(b \rightarrow \text{open } c) - B(b \rightarrow u\bar{c}s'). \]  

Method B:

\[ B(b \rightarrow \text{no open charm}) = R - B(b \rightarrow \text{open } \tau). \]
Here, $R$ is the remaining BR after reliable components have been subtracted,

\[
R \equiv B(b \to \text{no charm}) + B(b \to c\bar{s}') + B(b \to u\bar{s}') = 1 - B(b \to c(\tau \bar{\tau}) - B(b \to c\bar{d}') = 1 - BR_{s\ell}[2 + r_{\tau} + r_{ud}].
\] (11)

Theory provides $r_{\tau}$, $r_{ud}$, experiment $BR_{s\ell} = 0.105 \pm 0.005^{+22}_{-22}$, and $R = 0.35 \pm 0.05$ results. This result changes only minimally to

\[
R = 0.36 \pm 0.05,
\] (12)

once differences in the $B^-$ and $\overline{B}_d$ rates governed by $b \to c\bar{d}$ have been conservatively incorporated. Our prediction Eq. (12) for $R$ combines the most accurate information available from both theory and experiment.

The average of methods A and B is denoted by Method C:

\[
B(b \to \text{no open charm}) = \frac{1}{2}[1 + R - Y_{\text{open c}} - B(b \to u\bar{s}')],
\] (13)

where the flavor-blind quantity $Y_{\text{open c}} \equiv B(b \to c) + B(b \to \text{open } \bar{c})$. Because flavor-blind yields are better known than flavor-specific ones, Method C allows the most accurate prediction for $B(b \to \text{no open charm})$. Note that while Method A involves experimental data alone (with minimal theoretical input), Methods B and C require the theoretical prediction for $r_{ud}$. Method C reduces its sensitivity on theoretical input with regard to Method B, because of the factor 1/2. Table I summarizes our findings.

Why is $B(b \to \text{no open charm})$ enhanced over traditional expectations of $0.05 \pm 0.01^{+22}_{-22}$? New physics may provide a solution and could enhance the charmless $b \to s'$ transitions. But before concluding that, all Standard Model explanations must be exhausted first.

Non-perturbative effects could be responsible for $c\bar{c}$ pairs to be seen significantly as light hadrons. The $c\bar{c}$ pairs produced in $b \to c\bar{s}$ transitions have low invariant mass and are dominantly in a color-octet state. The predominantly $c\bar{c}$ color-octet configuration may have sizable overlap with the

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Table 1: Indirect estimates of no open charm in $B$ decays

| Method  | $B(b \to \text{no open charm})$ [CLEO] |
|---------|-------------------------------------|
| Method A| $0.15 \pm 0.05$                      |
| Method B| $0.17 \pm 0.06$                      |
| Method C| $0.16 \pm 0.04$                      |
wavefunction of $c\bar{c}$ hybrids, $H_c$, which are made of $c\bar{c}$ and glue. Although their masses could be beyond the open charm threshold, model-dependent selection rules suppress $H_c \rightarrow D^{(*)} \bar{D}^{(*)}$ transitions. Consequently, they could be narrow and could be seen sizably as light hadrons. That light hadron yield is probably governed significantly by resonant production of light gluonic hadrons. More generally, because the $b$-quark is sufficiently massive and decays in a gluon rich environment (provided, for instance, by the soft gluons emanating from the light spectator quark[s]), we anticipate copious production of gluonic hadrons and enhanced non-perturbative annihilation of $c\bar{c}$ pairs (see Figure (1b) in Ref. 32).

Perhaps the wavefunctions of light hadrons [$\pi, \rho, K^{(*)}$, etc.] have a non-negligible component of intrinsic $c\bar{c}$. The generic charmless mode is $B \rightarrow \bar{K} n \pi$ ($n \geq 1$), where no partial subset of final state particles reconstructs a charmed hadron. The $c\bar{c}$ component may have transformed itself into an intrinsic piece of decay products, and interference effects may be important. Because more excited light resonances have generally a larger intrinsic charm component than less excited states, it appears plausible that the $B \rightarrow \bar{K} n \pi$ processes feed through such more excited resonances. The end result of such resonances to have net zero strangeness, else the whole invariant mass $m_b$ of the $b \rightarrow c\bar{c}s$ process would be available to create strange resonances with intrinsic charm.

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*We expect those resonances to have net zero strangeness, else the whole invariant mass $m_b$ of the $b \rightarrow c\bar{c}s$ process would be available to create strange resonances with intrinsic charm.*
a scenario is very similar to the above mentioned possibility of charmed hybrid production. Nevertheless, they could be distinguished.

Charmed hybrids are predicted to have masses of about 4 GeV or above, while light resonances with an intrinsic $c\bar{c}$ component could be significantly lighter. Consequently, a detailed momentum spectrum of the recoiling $K^{(*)}$ in such $B$ decays may help in differentiating the various possibilities. A surplus of very high momentum $K^{(*)}$ is consistent with the production of excited resonances that contain intrinsic charm or with direct production of light gluonic hadrons. A high momentum $K^{(*)}$ excess (although less high than the aforementioned) may indicate $H_c$ production, while the momentum spectra of produced kaons in non-resonant $\bar{B} \rightarrow K n \pi$ processes will be different. Such and other non-perturbative effects must be carefully investigated.

Another solution is provided by a reduction of $B(D^0 \rightarrow K^- \pi^+)$ from presently accepted values, which would increase $n_c$ and would cause $B(b \rightarrow no \ open \ charm)$ to decrease towards traditional expectations. This and other systematic effects have been discussed in Ref.\textsuperscript{17}. Figure 3 emphasizes the importance of accurate measurements of $r_D$ using essentially only experimental input.

That figure plots $B(b \rightarrow no \ open \ charm)$ (Method A) and $r_{ud}$ as a function of $r_D$. The ALEPH measurement fully reconstructs both charm mesons in $\bar{B} \rightarrow D^0 \pi^-$ transitions, and thus suffers from low statistics. The existing data samples at $Z^0$-factories allow more accurate $B(b \rightarrow D)$ measurements. After selecting an enriched $b$-sample, one needs to reconstruct a single $D^0$ only, employ optimized flavor-tagging, and correct for $B^0 - \bar{B}^0$ mixing effects. (We add parenthetically that those data samples allow meaningful CP violating tests.) If sizable charged $B^+\pi^-$ data samples can be efficiently isolated, one could determine again $B(B^- \rightarrow D^- \pi)$ and $B(b \rightarrow D)$ without the need for a flavor-tag and for corrections due to $B^0 - \bar{B}^0$ mixing. The accurate determinations of $B(b \rightarrow D)$ are crucial for resolving the inclusive $B$ decay puzzles (see Figure 3), and should be pursued with high priority.

\section{Conclusions}

Under the traditional assumption of a tiny $B(b \rightarrow charmless)$, the accurately measured $BR_{s\ell} = 0.105 \pm 0.005$ allowed the prediction

\begin{equation}
 n_c = 1.30 \pm 0.05 ,
\end{equation}
Recent flavor-specific measurements opened up new aspects pertaining to this puzzle and allowed the indirect extraction of $B(b \to \text{no open charm})$ in a variety of ways. The results of the methods are consistent, strengthening our conclusion that the charmless yield in $B$ decays is enhanced over traditional estimates. Method C yields the most accurate prediction of

$$B(b \to \text{no open charm}) = 0.16 \pm 0.04.$$  (17)

This large charmless yield would show up as an enhanced fraction of $b$-decays, without a separate daughter charm vertex. We expect the underlying physics to be non-perturbative in nature, which causes a sizable fraction of $c\bar{c}$ pairs to be seen as light hadrons. The momentum spectrum of the involved $K^{(*)}$ may help in distinguishing among the various scenarios.

We touched upon the systematics of our analysis and considered the parameters $[B(b \to \text{no open charm}), r_{ud}, B(D^0 \to K^-\pi^+), r_D]$ and correlations among them. The prediction for $r_{ud}$ involve larger theoretical uncertainties than presently realized. Under the assumption of local duality, the dependence of the predicted $r_{ud}$ on the scale $\mu$ is large, and is not improved by going from leading-order to next-to-leading-order, see Figure 2. While the large scale dependence is troublesome, an even more disturbing aspect is the fact that duality assumes an inclusive rate based on 3 body phase-space, while the $b \to c \bar{u}d$ transitions proceed sizably as quasi-two body modes. Fortunately, $r_{ud}$ can be extracted from experimental measurements alone, which can be confronted with theory. More accurate determinations of $r_D$ or equivalently $B(b \to \bar{D})$ are possible from existing data samples at LEP/SLD/CLEO. They are invaluable in guiding us toward a more complete understanding of $B$-decays.

The $b \to c \bar{u}d$ transitions could be modelled as follows. For small invariant $\bar{u}d$ masses ($m_{\bar{u}d} \leq m_\tau$), the color-singlet $\bar{u}d$ pair hadronizes with little or no final state interactions. The factorization assumption can be justified, because by the time the $\bar{u}d$ forms a sizable color dipole [with which it could interact with its surrounding environment], it left the other debris of the $B$-decay far behind. The hadronization of those $\bar{u}d$ pairs can be determined from the well-studied $\tau$ decays, $\tau \to \nu + \bar{u}d$, which are dominated by the production of $\bar{u}d$ resonances. The $b \to c$ transitions can be modelled by HQET with input from semileptonic measurements and are seen dominantly as $(D, D^*, D^{**})$ resonances. Factorization is not as reliable for higher invariant $\bar{u}d$ masses. Fortunately, the $\bar{u}d$ invariant mass spectrum falls rapidly off at higher masses, as shown by a straightforward Dalitz plot. Assuming factorization, the vector contribution can be inferred from $e^+e^-$ measurements at the same c.m. energy, where the isospin 1 component has to be isolated from the data. The axial-vector component can be obtained from the relevant spectral function. We are in the process of developing a $b \to c \bar{u}d$ Monte Carlo simulation.
$B$ decays are a fertile ground for searching and discovering subtle hadronization effects. By utilizing the long lifetime of $b$-hadrons, vertex detectors can drastically reduce backgrounds. To fully explore multibody decays of $b$-hadrons it will be essential to not only have good $\pi/K/p$ separation, but the ability to detect $\pi^0, \eta(\prime), \gamma$ as well. An additional very important bonus will be a more optimal exploration of sizable CP violating effects residing in such multi-body $B$ decay modes. Especially striking effects within the CKM model are expected in $b \rightarrow d$ transitions.

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