REVIEW OF HADRONIC AND RARE B DECAYS

T.E. Browder

Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, U.S.A

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1 Introduction

We discuss new results on rare and hadronic B decays from the CLEO, CDF and LEP experiments.

2 Inclusive B Decays and Charm Counting

A complete set of measurements of inclusive B decays is now emerging from the CLEO experiment. When combined with observations of lepton-charmed particle correlations these will provide a full picture of the weak interaction mechanisms which operate in B decay. The measurements of branching fractions for inclusive B decays are given in Table 5.

Preliminary results on $B \to D^0 X$ and $B \to D^+ X$ branching fractions were shown at this conference. From these and earlier results[2],[3],[4], [5],[6], we can obtain n_c, the number of charm quarks produced per B decay. I have calculated the value of n_c using measurements from CLEO II alone and using world averages[7]. Since many of the inclusive measurements are limited by the systematic uncertainties in charmed meson absolute branching fractions, the CLEO II results do not completely dominate the world average. In Table 1, we give the value of n_c for the CLEO II experiment. We also a compute a world average for n_c by combining measurements from the CLEO 1.5, ARGUS and CLEO II experiments.

Table 1: Total Charm Yield in B Decay [%]

CLEO II	World Average
115.8 ± 5.26	111.7 ± 4.56

Table 2: $b \to c\bar{c}s$ Fraction [%]

CLEO II	World Average
17.9 ± 2.02	16.1 ± 1.76

Particle-lepton correlations can give important information on the production mechanisms operative in inclusive B decay. For instance last year, motivated by the low charm yield in inclusive B decay, the possibility of a new mechanism operative in $B \to$ baryon decay was suggested by Falk, Wise, and Dunietz[8]. The mechanism, internal W emission in $b \to c\bar{c}s$ decay, gives rise to $\Lambda_c^+ - \ell^+$ correlations whereas the usual $b \to c\bar{u}d$ mechanisms give the opposite $\Lambda_c^+ - \ell^-$ correlations. Note that the charge of the high momentum lepton is used to tag the flavor of the other B meson. A modest signal is observed in the wrong sign $\Lambda_c^+ - \ell^+$ correlation indicating that the ratio $b \to c\bar{c}s / b \to c\bar{u}d$ in B$\to$ baryon decays is $0.20 \pm 0.13 \pm 0.04$[4]. Similiarly the possibility of $B \to D_s^+$ production from $b \to c\bar{u}d$ processes with $s\bar{s}$ quark popping can be distinguished from direct $B \to D_s^+$ production from the quark level process $b \to c\bar{c}s$ by the sign of the $D_s - \ell$ correlation. A limit on the former possibility (i.e. $b \to c\bar{u}d$ with $s\bar{s}$ quark popping) can be deduced from the upper limit reported on $D_s^+ - \ell^+$ correlations at this conference ($< 31\%$ of the total)[10].

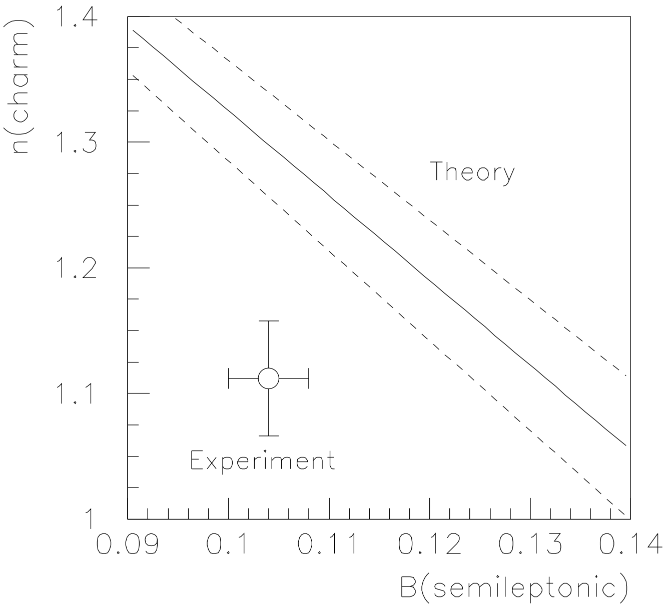

Figure 1: The charm yield per B decay versus the B semileptonic branching fraction. The point with error bars is the experimental world average. The solid line is the theoretical prediction. The dashed lines are upper bounds on the theoretical uncertainties.

In Table 2, we also give $\mathcal{B}(b \to c\bar{c}s)$ which is computed from the observed rates for $B \to D_s$, $B \to \psi$, $B \to \psi'$, and $B \to \Xi_c$ decays. The branching fraction is below 30%, the value which is theoretically required to accomodate the low value of the semileptonic branching fraction[11],[8],[9]. The possible contribution of $B \to D\bar{D}K$ decays, which corresponds to the quark level process $b \to c\bar{c}s$ with popping of a light quark pair, is not included. Buchalla, Dunietz, and Yamamoto have recently suggested that the latter mechanism may be significant[9]. This possibility leads to wrong sign $D - \ell$ correlations and is currently under investigation at CLEO[13].

Figure 1 shows a comparison of the world average value of n_c and the theoretical expectation from the parton model[12]. For the world average of the B semileptonic branching fraction, the expectation is $n_c \approx 1.3$. Thus, theory and experiment disagree. The origin of this discrepancy is still not well understood. A number of explanations have been suggested.

One possibility is a systematic flaws in the experimental determination of the yield of charm quarks. The charm meson absolute branching fractions can contribute a systematic uncertainty, although the errors from this source have been significantly reduced by the precise recent determinations of $\mathcal{B}(D^0 \to K^-\pi^+)$ and $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$. However, the absolute branching fraction scales for the D_s meson and Λ_c baryons are still quite uncertain. Since the inclusive branching ratios to these particles are small, a substantial change to the branching ratio scale would be required to significantly modify the charm yield.

Another possibility is a large production mechanism that contributes to the inclusive rate but that has not been measured or identified. Palmer and Stech have suggested[14], that $b \to c\bar{c}s$ followed by $c\bar{c} \to$ gluons, which in turn hadronize into a final state with no charm, has a large branching ratio. The charm content for this mechanism would not be properly taken into account. Another related suggestion is that the rate for the hadronic penguin diagram $b \to sg$ is larger than expected[15].

3 Color suppressed amplitude

We now discuss progress on determination of the strength and magnitude of the internal W emission or "color suppressed" amplitude. The evidence for the presence of this mechanism are $B \to \psi$ decays which result from internal W-emission ($b \to c\bar{c}s$). To date, there is no direct observation of the corresponding internal W-emission process $b \to c\bar{u}d$ which results in final states such as $\bar{B}^0 \to D^{(*)0}\pi^0$ and $\bar{B}^0 \to D^{(*)0}\eta^{(\prime)}$. Improved upper limits on these decay modes were reported at this conference[16]. The best limit

$$\mathcal{B}(\bar{B}^0 \to D^0\pi^0)/\mathcal{B}(\bar{B}^0 \to D^+\pi^-) < 0.11$$

is near the range expected from models $(0.03 - 0.08)$. Measurements of B^- decay modes, where both external and internal W-emission amplitudes contribute, give indirect information on the size of the color suppressed amplitude in $b \to c\bar{u}d$ and show that it has a positive sign[6].

Improved measurements of decays involving charmonia were reported at this conference by CLEO and CDF. A measurement of the polarization in their large and clean sample of reconstructed $\bar{B}^0 \to \psi K^{*0}$ events has been completed by CDF. They find

$$\Gamma_L/\Gamma_T = 0.65 \pm 0.10 \pm 0.04 \text{ (CDF)}.$$

This is consistent with but slightly lower than the two previous measurements from ARGUS and CLEO II. A new world average can also be calculated from these measurements,

$$\Gamma_L/\Gamma_T = 0.78 \pm 0.07 \text{ (World Average)}.$$

In addition, CDF reported the first measurement of polarization for the $B_s \to \psi\phi$ mode,

$$\Gamma_L/\Gamma_T = 0.56 \pm 0.21^{+0.02}_{-0.04} \text{ (CDF)}.$$

The CDF experiment also reported observation of a Cabibbo suppressed decay mode $B^+ \to \psi\pi^+$. They found 25 ± 8 events and performed a number of consistency checks to verify that these events did not originate from the kinematic reflection of $B^+ \to \psi K^+$. The ratio of branching fractions[18]

$$\mathcal{B}(B^+ \to \psi\pi^+)/\mathcal{B}(B^+ \to \psi K^+) = 4.9^{+1.9}_{-1.7} \pm 1.1\%$$

is consistent with an earlier CLEO observation and the updated result

$$\mathcal{B}(B^+ \to \psi\pi^+)/\mathcal{B}(B^+ \to \psi K^+) = 5.2 \pm 2.4\%$$

presented at this conference[19].

The factorization hypothesis works at the present level of experimental precision for $B \to D^*\pi^-$, $B \to D^*\rho^-, D^*a_1^-$ decays which are external W-emission $b \to c\bar{u}d$ processes with large energy release. It is difficult, however to simultaneously accomodate the value[6]

$$R = \mathcal{B}(B \to \psi K^*)/\mathcal{B}(B \to \psi K) = 1.68 \pm 0.33$$

and the observed polarization in $B \to \psi K^*$ in models based on factorization[20,21]. It is open question as to whether this indicates that factorization breaks down in internal W-emission or that there is some other flaw in the models.

4 Rare B Decays and Gluonic Penguins

The CLEO experiment has recently presented a measurement of the inclusive $b \to s\gamma$ branching fraction. So far, no unambiguous evidence for the gluonic analogue, $b \to s$ gluon, has been found.

CLEO has recently updated their measurement of the sum of the branching fractions for $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$, they find a signal which contains

$17.2^{+5.6+2.2}_{-4.9-2.5}$ events which corresponds to a branching fraction

$$\mathcal{B}(B^0 \to \pi^+\pi^-, K^+\pi^-) = (1.8^{+0.6+0.2}_{-0.5-0.3} \pm 0.2) \times 10^{-5}$$

There is insufficient statistics to claim a signal in either of the individual modes and upper limits of

$$\mathcal{B}(B^0 \to \pi^+\pi^-) < 2.0 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to K^+\pi^-) < 1.7 \times 10^{-5}$$

are given. Therefore it is not possible to isolate the contributions of the spectator and penguin amplitudes.

The LEP experiments have begun to achieve an interesting sensitivity to rare B decays. Limits on these two body charged modes in the range $(4 - 8) \times 10^{-5}$ have been obtained by ALEPH, and OPAL. The utility of the silicon vertex detectors is demonstrated by the low backgrounds and sensitivities achieved by ALEPH in their search for higher multiplicity rare B decays such as $\bar{B} \to 2\pi^+2\pi^-$). DELPHI presented evidence of a signal in the sum of two body modes. The observed signal, which contains 3 events with an estimated background of 0.18 events, corresponds to the branching fraction

$$\mathcal{B}(B^0 \to \pi^+\pi^-, K^+\pi^-) = (2.5 \pm 1.4) \times 10^{-5}$$

and is consistent with the CLEO measurement. The L3 experiment take advantage of their electromagnetic calorimetry to obtain limits on rare B decays with multi-neutrals (e.g. $\bar{B} \to \eta\pi^0$). Their limits on modes in this class are in the range $(8 \times 10^{-5}) - (3 \times 10^{-4})$.

It is also possible to constrain the penguin amplitude by searching for $b \to s\bar{s}s$ decays such as $B \to \phi K^0$ which do not have contributions from other processes. CLEO has searched for the decay modes $\bar{B} \to \phi K^{(*)}$ and obtained limits on their branching fractions in the range $(1.2 - 8.8) \times 10^{-5}$.

Recently another method for constraining $b \to s$ gluon using inclusive processes has been introduced by CLEO. It is possible to examine the endpoint region in inclusive ϕ production beyond the kinematic limit for $b \to c$ processes. This corresponds roughly to the range $2.7 > p(\phi) > 2.0$ GeV.

Two experimental methods have been applied[23]. One can search for an excess in the endpoint region after applying loose event shape cuts. This method has a minimal dependence on the model of the X_s hadronization. No signal is observed. This method gives an upper limit of $\mathcal{B}(B \to X_s\phi) < 2.2 \times 10^{-4}$ for $2.7 > p(\phi) > 2.0$ GeV An alternate approach is to combine ϕ mesons with n charged pions and a neutral pion, where $n = 1 - 4$, and then form the beam constrained mass or energy difference. No attempt is made to correct for misidentification of decay modes. Then combinations which are inconsistent with the B mass and the beam energy are discarded in order to suppress continuum. This gives an upper limit of $\mathcal{B}(B \to X_s\phi) < 1.1 \times 10^{-4}$ for $M(X_s) < 2.0$ GeV.

To convert these results into limits on the total rate $\mathcal{B}(B \to X_s\phi)$ a theoretical model is required. We have used the model of Deshpande et al., which implies that most of the rate is concentrated in quasi two body modes which produce ϕ mesons in the high momentum window[24]. Only a small correction is required, and the most stringent limit is obtained by the second method which gives $\mathcal{B}(B \to X_s\phi) < 1.3 \times 10^{-4}$ at the 90% confidence level. More theoretical work is required to understand the implications for $\mathcal{B}(b \to s$ gluon).

The inclusive method of studying rare decays described here can be extended to $B \to K_s$, $B \to K^*$, $B \to \eta^{(')}$ transitions in order to search for other signatures of gluonic penguins.

5 Conclusion

A complete picture of inclusive B decays is emerging from recent measurements by the CLEO experiment. The experimental result for the charm yield per B decay (n_c) is consistent with the naive expectation that 1.15 charm quarks are produced per b decay. However, it does not support the proposals which suggest that at least 1.3 quarks should be produced per b decay. Recent theoretical efforts require such a high charm yield in order to explain the discrepancy between theoretical calculations and experimental measurements of the inclusive semileptonic rate, $\mathcal{B}(B \to X\ell\nu)$

The CDF results on B decay modes with charmonia presented at this conference provide compelling evidence for the utility of silicon vertex detectors in B physics and indicate that CDF has now begun to make major contributions to the study of B *decay*. The theoretical problems of interpreting the data and understanding whether factorization is operative in internal W-emission however remain.

The long struggle to isolate and measure the gluonic penguin amplitude in B decay continues. This is an essential component of the program of extracting physics from measurements of CP asymmetries at future facilities.

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Table 3: Branching fractions (%) of inclusive B decays

Particle	ARGUS	CLEO 1.5	CLEO	Average
$\bar{B} \to \bar{D}^0 X$	$49.7 \pm 3.8 \pm 6.4 \pm 2.6$	$59.7 \pm 3.2 \pm 3.6 \pm 3.1$	$64.5 \pm 2.1 \pm 1.4 \pm 1.8$	61.9 ± 2.6
$\bar{B} \to D^- X$	$23.0 \pm 3.0 \pm 4.4 \pm 1.5$	$24.9 \pm 3.3 \pm 2.0 \pm 1.6$	$23.5 \pm 1.2 \pm 0.8 \pm 2.3$	23.8 ± 2.1
$\bar{B} \to D_s^- X$	$8.3 \pm 1.1 \pm 0.9 \pm 1.0$	$8.7 \pm 1.3 \pm 1.0$	$12.1 \pm 0.4 \pm 0.9 \pm 1.4$	$10.3 \pm 0.7 \pm 1.2$
$\bar{B} \to \psi X$	$1.25 \pm 0.19 \pm 0.26$	$1.31 \pm 0.12 \pm 0.27$	$1.12 \pm 0.04 \pm 0.06$	1.14 ± 0.07
$\bar{B} \to \psi X$ (direct)	0.95 ± 0.27		0.81 ± 0.08	0.82 ± 0.08
$\bar{B} \to \psi' X$	$0.50 \pm 0.19 \pm 0.12$	$0.36 \pm 0.09 \pm 0.13$	$0.34 \pm 0.04 \pm 0.03$	0.35 ± 0.05
$\bar{B} \to \chi_{c1} X$	$1.23 \pm 0.41 \pm 0.29$		$0.40 \pm 0.06 \pm 0.04$	0.42 ± 0.07
$\bar{B} \to \chi_{c1} X$ (direct)			0.37 ± 0.07	0.37 ± 0.07
$\bar{B} \to \chi_{c2} X$			$0.25 \pm 0.10 \pm 0.03$	0.25 ± 0.10
$\bar{B} \to \eta_c X$			< 0.90 (90% C.L.)	< 0.90 (90% C.L.)
$\bar{B} \to \Lambda_c^- X$	$7.0 \pm 2.8 \pm 1.4 \pm 2.1$	$6.3 \pm 1.2 \pm 0.9 \pm 1.9$		$6.4 \pm 1.3 \pm 1.9$
$\bar{B} \to \Xi_c^+ X$			1.5 ± 0.7	1.5 ± 0.7
$\bar{B} \to \Xi_c^0 X$			2.4 ± 1.3	2.4 ± 1.3

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