Hadronic Decays and Lifetimes of B and D Mesons

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We review recent experimental results on hadronic decays and lifetimes of hadrons containing b and c quarks.[1] We discuss charm counting and the semileptonic branching fraction in B decays, the color suppressed amplitude in B and D decay, and the search for gluonic penguins in B decay.

1 Charm counting and the semileptonic branching fraction

1.1 The Experimental Observations

A complete picture of inclusive B decay is beginning to emerge from recent measurements by CLEO II and the LEP experiments. These measurements can be used to address the question of whether the hadronic decay of the B meson is compatible with its semileptonic branching fraction.

Three facts emerge from the experimental examination of inclusive B decay:

$$n_c = 1.15 \pm 0.05$$

where n_c is the number of charm quarks produced per B decay taking an average of ARGUS, CLEO 1.5, and CLEO II results and using $\mathcal{B}(D^0 \to K^-\pi^+) = (3.76 \pm 0.15\%)$.

$$\mathcal{B}(B \to X\ell\nu) = 10.23 \pm 0.39\%$$

This value is the average of the CLEO and ARGUS model independent measurements using dileptons. The third quantity is calculated from the inclusive $B \to D_s$, $B \to (c\bar{c})X$, and $B \to \Xi_c$ branching fractions,

$$\mathcal{B}(b \to c\bar{c}s) = 0.158 \pm 0.028\%.$$

It is determined assuming no contribution from D production, an assumption which can be checked using data.

1.2 Theoretical Interpretation

In the usual parton model, it is difficult to accomodate a low semileptonic branching fraction unless the hadronic width of the B meson is increased.[3]

The explanations for the semileptonic branching fraction which have been proposed can be formulated by expressing the hadronic width of the B meson in terms of three components:

$$\Gamma_{hadronic}(b) = \Gamma(b \to c\bar{c}s) + \Gamma(b \to c\bar{u}d) + \Gamma(b \to s\, g).$$

If the semileptonic branching fraction is to be reduced to the observed level, then one of these components must be enhanced.

A large number of explanations have been proposed in the last few years. These explanations can be logically classified as follows:

1. An enhancement of $b \to c\bar{c}s$ due to large QCD corrections or the breakdown of local duality.[4,5,6,7]
2. An enhancement of $b \to c\bar{u}d$ due to non-perturbative effects. [8,9,10,11]
3. An enhancement of $b \to s\, g$ or $b \to d\, g$ from New Physics.[12,13,14]
4. The cocktail solution: For example, if both the $b \to c\bar{c}s$ and the $b \to c\bar{u}d$ mechanisms are increased, this could suffice to explain the inclusive observations.
5. There might also be a systematic experimental problem in the determination of either n_c, $\mathcal{B}(b \to c\bar{c}s)$, or $\mathcal{B}(B \to X\ell\nu)$.[15]

1.3 Other experimental clues

Inclusive charm particle-lepton correlations can be used to probe the B decay mechanism and give further insight into this problem. High momentum leptons are used $p_\ell > 1.4$ GeV to tag the flavor of the B. The angular correlation between the meson and the lepton is then employed to select events in which the tagging lepton and meson are from different Bs.

For example, the sign of Λ_c-lepton correlations distinguishes between the $b \to c\bar{u}d$ and the $b \to c\bar{c}s$ mechanisms. Similiarly, examination of D_s-lepton correlations shows that most D_s mesons originate from $b \to c\bar{c}s$ rather than from $b \to c\bar{u}d$ with $s\bar{s}$ quark popping at the lower vertex. The same experimental technique can also be applied to D-lepton correlations.

The conventional $b \to c\bar{u}d$ mechanism which was *previously assumed* to be responsible for all D production in B decay will give $D - \ell^+$ correlations. If a significant fraction of D mesons arise from $b \to c\bar{c}s$ with light quark popping at the upper vertex. This new mechanism proposed by Buchalla, Dunietz, and Yamamoto will give $D - \ell^-$ correlations.[5]

Preliminary results of this study have been presented by CLEO II which finds, $\Gamma(B \to D\ X)/\Gamma(B \to \bar{D}X) = 0.107 \pm 0.029 \pm 0.018$.[16] This implies a new contribution to the $b \to c\bar{c}s$ width

$$\mathcal{B}(B \to DX) = 0.081 \pm 0.026.$$

ALEPH finds evidence for $B \to D^0\bar{D}^0X + D^0D^{\mp}X$ decays with a substantial branching fraction of $12.8 \pm 2.7 \pm 2.6\%$.[17] DELPHI reports the observation of $B \to D^{*+}D^{*-}X$ decays with a branching fraction of $1.0 \pm 0.2 \pm 0.3\%$.[19] Since CLEO has set upper limits on the Cabibbo suppressed exclusive decay modes $B \to D\bar{D}$ and $B \to D^*\bar{D}^*$ in the 10^{-3} range,[20] this implies that the signals observed by ALEPH and DELPHI involve the production of a pair of D mesons and additional particles. The rate observed by ALEPH is consistent with the rate of wrong sign D-lepton correlation reported by CLEO. It is possible that these channels are actually resonant modes of the form $B \to DD_s^{**}$ decays, where the p-wave D_s^{**} or radially excited $D_s^{'}$ decays to $\bar{D}^{(*)}\bar{K}$.

We can now recalculate

$$\mathcal{B}(b \to c\bar{c}s) = 0.239 \pm 0.038,$$

which would suggest a larger charm yield ($n_c \sim 1.24$). This supports hypothesis (1), large QCD corrections in $b \to c\bar{c}s$. *BUT the charm yield n_c as computed in the usual way is unchanged.* The $B \to D\bar{D}K$ source was properly accounted for in the computation of n_c. This suggests that the experimental situation is still problematic. Is there an error in the normalization $\mathcal{B}(D^0 \to K^-\pi^+)$ or is there still room for enhanced $\mathcal{B}(b \to cu\bar{d})$?

We note that ALEPH has recently reported a value for n_c in $Z \to b\bar{b}$.[18] They find $n_c^Z = 1.230 \pm 0.036 \pm 0.038 \pm 0.053$. The rate of D_s and Λ_c production is significantly higher than what is observed at the $\Upsilon(4S)$. It is not clear whether the quantity being measured is the same as n_c at the $\Upsilon(4S)$, which would be the case if the spectator model holds and if the contribution of B_s and Λ_b could be neglected. OPAL has reported a somewhat lower value of n_c.

There are other implications of these observations. A B decay mechanism with a $\mathcal{O}(10\%)$ branching fraction has been found which was not previously included in the CLEO or LEP Monte Carlo simulations of B decay. This may have consequences for other analyses of particle-lepton correlations. For example, CLEO has re-examined the model independent dilepton measurement of $\mathcal{B}(B \to X\ell\nu)$. Due to the lepton threshold of 0.6 GeV and the soft spectrum of leptons, that measurement is fortuitously unchanged.

2 The sign of the color suppressed amplitude and lifetimes

The sign and magnitude of the color suppressed amplitude can be determined using several classes of decay modes in charm and bottom mesons. The numerical determination assumes factorization and uses form factors from various phenemonological models.

For D decay one uses exclusive modes such as $D \to K\pi$, $D \to K\rho$ etc., and obtains

$$a_1 = 1.10 \pm 0.03,\ a_2 = -0.50 \pm 0.03$$

The destructive interference observed in two body D^+ decays leads to the D^+-D^0 lifetime difference.

For B decay, one can find the magnitude of $|a_1|$ from the branching fractions for the decay modes $\bar{B}^0 \to D^{(*)+}\pi^-$, $\bar{B}^0 \to D^{+(*)}\rho^-$. This gives $|a_1| = 1.06 \pm 0.03 \pm 0.06$. One can also extract $|a_1|$ from measurements of branching fractions $B \to D^{+,(0)}D_s^{(*)-}$. The magnitude $|a_2|$ can be determined from the branching fractions for $B \to \psi K^{(*)}$. This yields $|a_2| = 0.23 \pm 0.01 \pm 0.01$.

The value of a_2/a_1 can be found by comparing B^- decays where both the external and spectator diagrams contribute to $\bar{B}^0$ decays where only the external spectator decays contribute. The model of Neubert et al. predicts the following ratios:

$$R_1 = \frac{\mathcal{B}(B^- \to D^0\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^+\pi^-)} = (1 + 1.23a_2/a_1)^2 \quad (1)$$

$$R_2 = \frac{\mathcal{B}(B^- \to D^0\rho^-)}{\mathcal{B}(\bar{B}^0 \to D^+\rho^-)} = (1 + 0.66a_2/a_1)^2 \quad (2)$$

$$R_3 = \frac{\mathcal{B}(B^- \to D^{*0}\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)} = (1 + 1.29a_2/a_1)^2 \quad (3)$$

$$R_4 = \frac{\mathcal{B}(B^- \to D^{*0}\rho^-)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\rho^-)} \approx (1 + 0.75a_2/a_1)^2 \quad (4)$$

Using the latest branching fractions, we find

$$a_2/a_1 = 0.26 \pm 0.05 \pm 0.09,$$

where the second error is due to the uncertainty ($\sim 20\%$) in the relative production of B^+ and B^0 mesons at the $\Upsilon(4S)$. This is consistent with $|a_2|/|a_1|$ where $|a_2|$ is computed from $B \to \psi$ modes and $|a_1|$ is computed from $\bar{B}^0 \to D^{(*)}\pi, D^{(*)}\rho$ modes.

If the constructive interference which is observed in these B^- decays is present in all B^- decays, then we expect a significant B^--B^0 lifetime difference ($\tau_{\bar{B}} < \tau_{B^0}$), of order $15 - 20\%$. This is only marginally consistent with experimental measurements of lifetimes; the world average computed in our review[1] is

$$\tau_{B^-}/\tau_{B^0} = 1.00 \pm 0.05.$$

It is possible that the hadronic B^- decays that have been observed so far are atypical. The remaining higher multiplicity B^- decays could have destructive interference or no interference. Or perhaps there is a mechanism which also enhances the $\bar{B}^0$ width to compensate for the increase in the B^- width and which maintains the B^+/B^0 lifetime ratio near unity. Such a mechanism would be relevant to the charm counting and semileptonic branching fraction problem. In either case, there will be experimental consequences in the pattern of hadronic B branching fractions.

3 The search for the gluonic penguin

It is important to measure the size of $\mathcal{A}(b \to s\ g)$, the amplitude for the gluonic penguin, in order to interpret the CP violating asymmetries which will be observed at future facilities. Gluonic penguin modes will also be used to search for direct CP violation.

CLEO-II has observed a signal in the sum of $\bar{B}^0 \to K^+\pi^-$ and $\bar{B}^0 \to \pi^+\pi^-$ with a branching fraction of $(1.8^{+0.6+0.2}_{-0.5-0.3}) \times 10^{-5}$ and for the individual modes $\mathcal{B}(B^0 \to \pi^+\pi^-) < 2.0 \times 10^{-5}$, $\mathcal{B}(B^0 \to K^+\pi^-) < 1.7 \times 10^{-5}$. Similiar results with consistent branching fractions have been reported by DELPHI[21] and ALEPH[22]. CLEO-II has also observed a signal in the sum of $B^- \to K^-\omega$ and $B^- \to \pi^-\omega$.[23] The combined branching fraction is $(2.8 \pm 1.1 \pm 0.5) \times 10^{-5}$. In all of these cases, due to the paucity of events and the difficulty of distinguishing high momentum kaons and pions, the conclusion is that either $b \to u$ or $b \to s\ g$ decays or a combination of the two has been observed.

Another approach using quasi-inclusive decays is described in a recent CLEO contribution.[24] At the $\Upsilon(4S)$, two body decays from $b \to s\ g$ can be distinguished from $b \to c$ decays by examination of the inclusive particle momentum spectrum; the $b \to s\ g$ decays populate a region beyond the kinematic limit for $b \to c$. This approach has been applied to inclusive η', K_s, and ϕ production.

A search for inclusive signatures of $b \to s$ gluon rather than exclusive signatures has two possible advantages. The inclusive rate may be calculable from first principles and is expected to be at least an order of magnitude larger than the rate for any exclusive channel. For example, the branching fraction for $b \to sq\bar{q}$ (where $q = u,\ d,\ s$) is $\mathcal{O}(1\%)$[25,26] and the branching fraction for the inclusive process $b \to s\bar{s}s$ is expected to be $\sim 0.23\%$ in the Standard Model[26], while low multiplicity decay modes such as $\bar{B}^0 \to \phi K_s$ or $\bar{B}^0 \to K^-\pi^+$ are expected to have branching fractions of order 10^{-5}. The disadvantage of employing an inclusive method is the severe continuum background that must be subtracted or suppressed.

The decay $B \to \eta' X_s$, where X_s denotes a meson containing an s quark, is dominated by the gluonic penguins, $b \to sg^*$ $g^* \to s\bar{s}$, $g^* \to u\bar{u}$ or $g^* \to d\bar{d}$. The decay $B \to K_s X$, where X denotes a meson which contains no s quark, arises from a similiar gluonic penguin, $b \to sg^* \to s\bar{d}d$.

An analogous search for $b \to sg^*$, $g^* \to s\bar{s}$ was carried out by CLEO using high momentum ϕ production[29]. In the search for high momentum ϕ production, limits were obtained using two complementary techniques. A purely inclusive technique with shape cuts gave a limit $\mathcal{B}(B \to X_s\phi) < 2.2 \times 10^{-4}$ for $2.0 < p_\phi < 2.6$ GeV. Using the B reconstruction technique, in which combinations of the ϕ candidate, a kaon, and up to 4 pions were required to be consistent with a B candidate, gave a limit of $\mathcal{B}(B \to X_s\phi) < 1.1 \times 10^{-4}$ for $M_{X_s} < 2.0$ GeV, corresponding to $p_\phi > 2.1$ GeV. These results can be compared to the Standard Model calculation of Deshpande *et al.*[27], which predicts that the branching fraction for this process should lie in the range $(0.6 - 2.0) \times 10^{-4}$ and that 90% of the ϕ mesons from this mechanism will lie in the range of the experimental search. Ciuchini *et al.*[28] predict a branching fraction for $\mathcal{B}(B \to X_s\phi)$ in the range $(1.1 \pm 0.9) \times 10^{-4}$. One sees that the sensitivity of the inclusive method is nearly sufficient to observe a signal from Standard Model $b \to s\ g$.

Using the purely inclusive technique, a modest excess was observed in the signal region for quasi two-body $B \to \eta' X_s$ decays. A 90% confidence level upper limit of for the momentum interval $0.39 < x_{\eta'} < 0.52$,

$$\mathcal{B}(B \to \eta' X_s) < 1.7 \times 10^{-3}$$

is obtained. Further work is in progress to improve the sensitivity in this channel. Examination of high momentum K_s production gives a 90% confidence level upper limit of

$$\mathcal{B}(B \to K_s X) < 7.5 \times 10^{-4}$$

for $0.4 < x_{K_s} < 0.54$. More theoretical work is required to convert these limits into constraints on $b \to s\ g^*, g^* \to q\bar{q}$.

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