# A Review of Some Results in Heavy Quark Physics [†]

*G.D. Gollin*

University of Illinois, Urbana, IL 61801 USA

(CLEO Collaboration)

I will review recent progress concerning leptonic decay constants for heavy mesons, semileptonic B decay form factors, determinations of $V_{cb}$, and tests of factorization. There has been some disagreement between experiment and theory concerning the average number of charmed particles expected in B decays; I will report on the current status of this tempest-in-a-teapot. Please see the conference reports of other speakers concerning rare decays, $D^0 - \bar{D}^0$ mixing limits, $V_{ub}$ measurements $B - \bar{B}$ oscillations, particle lifetimes, and production mechanisms.

## Leptonic decay constants

The leptonic decay rate for pseudoscalar mesons can be written

$$\Gamma\left(P \to \ell\nu_\ell\right) \approx \frac{G_F^2 \left|V_{ij}\right|^2}{8\pi} f_P^2 m_\ell^2 m_P \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 .$$

Here, $m_\ell$ and $m_P$ are the lepton and meson masses, while $G_F$ is the Fermi constant and $V_{ij}$ the appropriate CKM matrix element. If $|V_{ij}|$ is known, a measurement of $\Gamma$ yields a value for $f_P$. Decay constants extracted from leptonic decay rates are needed to interpret other measurements, such as the determination of $V_{td}$ from $B-\bar{B}$ mixing. Lattice gauge calculations suggest that $f_{D_S} \sim (200 - 220) \pm \sim 30\, MeV$ and $f_{D_S}/f_D \approx 1.1$ while $f_B \sim (150 - 170) \pm \sim 30\, MeV$ and $f_{B_S}/f_B \approx 1.1$. Expectations for rates are shown in Table 1. Helicity suppression is responsible for the large differences in the decay rates.

| | e | $\mu$ | $\tau$ |
|---|---|---|---|
| $D^+$ | $10^{-8}$ | $10^{-4}$ | $10^{-4}$ |
| $D_S^+$ | $10^{-7}$ | $10^{-3}$ | $10^{-2}$ |
| $B^+$ | $10^{-11}$ | $10^{-7}$ | $< 10^{-4}$ |

Table 1: Expectations for various leptonic decay rates

$D^+ \to \mu^+\nu$

This is a hard mode to observe due to Cabibbo suppression: $|V_{cd}|^2 \approx 0.05$. BES[1] claims to observe one event at $\sqrt{S} = 4.03\, GeV$ in the channel $e^+e^- \to D^{*+}D^-$, $D^{*+} \to D^0\pi$ (with $D^0 \to K^-\pi$), $D^- \to \mu\nu$. The soft $\pi^+$ from the $D^{*+}$ is not observed. The analysis plots the missing mass recoiling against the $\mu$ and tagging D: one expects smaller missing

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mass for signal than for background events, which have an undetected $K_L$ or $\pi^0$. BES concludes that $B\left(D \to \mu\nu\right) = \left(0.08^{+0.16\ +0.05}_{-0.05\ -0.02}\right)\%$ so that $f_D = \left(300^{+180\ +80}_{-150\ -40}\right)\ MeV$.

$D_S \to \ell\nu$

CLEO[2], DELPHI[3], L3[4], BES[34], WA75[35], and Fermilab E653[36] have presented results, summarized in Table 2. CLEO observes $D_S^{*+} \to \gamma D_S^+$, $D_S^+ \to \mu\nu$ and requires a stiff $\mu$ to eliminate $b \to c$ backgrounds. Signal events are recognized by assigning $p_\nu = p_{miss}$, $E_\nu = E_{miss}$ and requiring that $\Delta m \equiv m_{\gamma\mu\nu} - m_{\mu\nu} \approx 144\,MeV$. The signal is normalized to $\Gamma\left(D_S^+ \to \phi\pi^+\right)$. Backgrounds have a hadron faking a $\mu$, or a random $\gamma$ combined with a real $D$ (or $D_S$) leptonic decay. CLEO observes $47 \pm 10$ $D_S \to \mu\nu$ and $9740 \pm 620 \pm 580$ $D_S \to \phi\pi$, concluding that $\Gamma\left(\mu\nu\right)/\Gamma\left(\phi\pi\right) = .184 \pm .038 \pm .038$ so that $f_{D_S} = (284 \pm 30 \pm 30 \pm 16)\ MeV$.

DELPHI studies $D_S^* \to \gamma D_S$, $D_S \to \tau\nu$, $\tau \to \ell\bar{\nu}_\ell\nu$ and uses an impact parameter cut to reduce $b \to c$ backgrounds. Their analysis requires significant missing energy in the lepton hemisphere: $E_{miss} > 15\,GeV$. Reconstruction of the $D_S$ 4-momentum uses $p_{miss}$ and assumes $m_{D_S}$. Like CLEO, DELPHI identifies its signal based on $\Delta m \approx 144\,MeV$. Most events are expected to be $\tau\nu$ decays, with about one tenth coming from $\mu\nu$ final states. Backgrounds from $b\bar{b}$ and $c\bar{c}$ decays are simulated and subtracted. From $10.8 \pm 5.4$ events, they calculate $B\left(D_S \to \tau\nu\right) = (8.5 \pm 4.2 \pm 2.6)\%$ so that $f_{D_S} = (330 \pm 95)\ MeV$.

L3's analysis is similar to DELPHI's. They observe $15.6 \pm 6.0 \pm 3.7$ $D_S \to \tau\nu$, $\mu\nu$ and calculate $B\left(D_S \to \tau\nu\right) = (7.4 \pm 2.8 \pm 1.6 \pm 1.8)\ \%$ and $f_{D_S} = (309 \pm 58 \pm 33 \pm 38)\ MeV$.

| | $\mu\nu$ (%) | $\tau\nu$ (%) | $f_{D_S}$ (MeV) |
|---|---|---|---|
| CLEO[2] | $0.64 \pm 0.13 \pm 0.13 \pm 0.07$ | | $284 \pm 30 \pm 30 \pm 16$ |
| DELPHI[3] | | $8.5 \pm 4.2 \pm 2.6$ | $330 \pm 95$ |
| L3[4] | | $7.4 \pm 2.8 \pm 1.6 \pm 1.8$ | $309 \pm 58 \pm 33 \pm 38$ |
| BES[34] | $1.5^{+1.1\ +0.3}_{-0.8\ -0.2}$ | | |
| WA75[35] | $0.38^{+0.17}_{-0.13} \pm 0.12 \pm 0.07$ | | $232 \pm 45 \pm 20 \pm 48$ |
| E653[36] | $0.31 \pm 0.12 \pm 0.06 \pm 0.06$ | | $194 \pm 35 \pm 20 \pm 14$ |
| Average (as $\mu\nu$) | $.50 \pm 0.08 \pm 0.09$ | | $251 \pm 30$ |

Table 2: Measurements of $D_S \to \tau\nu$, $\mu\nu$

$B \to \ell\nu$

This decay mode is Cabibbo suppressed relative to $b \to c$ decays: $|V_{ub}/V_{cb}|^2 \sim 0.006$. 90% confidence limits[4,5,6] on $B \to \tau\nu$ are shown in Table 3. Though limits on the $\mu\nu$ branching ratio are considerably better ($\sim 10^{-5}$), they are still far from the expected Standard Model rate.

## Semileptonic form factors for pseudoscalar decays

The pseudoscalar meson semileptonic decay rate depends on the spin of the final state daughter meson. For pseudoscalar-to-pseudoscalar decays,

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\left|V_{ij}\right|^2 p_{P'}^3}{24\pi^3}\left\{\left|f_+\left(q^2\right)\right|^2 + m_\ell^2\left|f_-\left(q^2\right)\right|^2\right\}$$

| | 90% c.l. |
|---|---|
| CLEO[5] | $< 2.2 \times 10^{-3}$ (90% c.l.) |
| ALEPH[6] | $< 1.6 \times 10^{-3}$ (90% c.l.) |
| L3[4] | $< 5.7 \times 10^{-4}$ (90% c.l.) |
| Standard Model | $< 10^{-4}$ |

Table 3: Limits on the branching ratio for $B \to \tau\nu$ decays

where $q^2$ is $(p^\mu_{P'} - p^\mu_P)^2$, largest when the daughter $P'$ is at rest in the parent meson's rest frame. Theory predictions are most reliable at large $q^2$, but the rate, proportional to $p^3_{P'}$, is small. Since $f_-(q^2)$ is small, it is often neglected in discussions of results.

Semileptonic decay rates into vector mesons include $q^2$ and angular dependences. Different (but equivalent) form factor descriptions are sometimes convenient for different decays: $\{H_\pm(q^2), H_0(q^2)\} \Leftrightarrow \{V(q^2), A_1(q^2), A_2(q^2)\} \Leftrightarrow \left\{R_1\, R_2, \rho^2_{A_1}\right\}$.

*$D$, $D_S$ semileptonic form factors*

It is common to assume a single-pole $q^2$ dependence for the form factors $f_\pm$ and $A_1$, $A_2$:

$$F(q^2) \;=\; F(0)\Big/\left(1 - q^2\Big/m^2_{pole}\right)$$

One expects the pole mass to be close to that for a low mass $c\bar{s}$ state with the correct quantum numbers. (Since final state mesons are light, HQET cannot be used to describe $D$, $D_S$ decays.) The magnitude of $f_+(0)$ can be extracted from the total decay rate. Interest in the $D$ and $D_S$ form factors stems from their utility as a check of strong interaction phenomenology. Are predicted relationships among the form factors verified by experimental data? Early results (~1990) seemed to cast doubt on some of the models.

Results for $D \to K\ell\nu$ form factors, summarized in Table 4, are dominated by CLEO[7], with 2700 events, and Fermilab E687[8] with 1897 events. In $D \to K^*\ell\nu$ and $D_S \to \phi\ell\nu$ decays one assumes a pole form $q^2$ dependence for the form factors and defines

$$r_V \equiv \frac{V(0)}{A_1(0)},\; r_2 \equiv \frac{A_2(0)}{A_1(0)}\,.$$

$K^{*0}\ell\nu$ measurements by FNAL E791[9] with 3000 $K^{*0}e\nu$ events and E687[10] with $875 \pm 44$ $K^{*0}\mu\nu$ events are shown in Table 5. Results concerning $D_S \to \phi\ell\nu$ decays (expected to resemble those for $K^{*0}\ell\nu$) are considerably less precise, and are shown in Table 6.

| | Pole mass (GeV) | $f_+(0)$ |
|---|---|---|
| E687[8] | $1.87\,^{+0.11\,+0.07}_{-0.08\;0.06}$ | $0.71 \pm 0.03 \pm 0.03$ |
| CLEO[7] | $2.00 \pm 0.12 \pm 0.18$ | $0.77 \pm 0.01 \pm 0.04$ |
| APE[37] (LGT calculation) | | $0.78 \pm 0.08$ |
| ELC[38] (LGT calculation) | | $0.60 \pm 0.15 \pm 0.07$ |

Table 4: $D \to K\ell\nu$ form factors

| | $r_V$ | $r_2$ |
|---|---|---|
| E687[10] | $1.74 \pm 0.27 \pm 0.28$ | $0.78 \pm 0.18 \pm 0.10$ |
| E791[9] | $1.84 \pm 0.11 \pm 0.08$ | $0.71 \pm 0.08 \pm 0.09$ |
| APE[37] (LGT calculation) | $1.61 \pm 0.42$ | $0.71 \pm 0.50$ |
| UKQCD[39] (LGT calculation) | $1.44^{+.45}_{-.24}$ | $.94^{+.17}_{-.25}$ |

Table 5: $D \to K^{*0}\ell\nu$ form factors

| | $r_V$ | $r_2$ |
|---|---|---|
| E653[36] (19 $\mu$) | $2.3^{+1.1}_{-0.9} \pm 0.4$ | $2.1^{+0.6}_{-0.5} \pm 0.2$ |
| E687[11] (90 $\mu$) | $1.8 \pm 0.9 \pm 0.2$ | $1.1 \pm 0.8 \pm 0.1$ |
| CLEO[12] (474 e) | $0.9 \pm 0.6 \pm 0.3$ | $1.4 \pm 0.5 \pm 0.4$ |
| average | $1.4 \pm 0.5$ | $1.6 \pm 0.4$ |

Table 6: $D_S \to \phi\ell\nu$ form factors

*$B \to D^{(*)}\ell\nu$ semileptonic form factors*

Thanks to heavy quark effective theory, accurate measurements of the B semileptonic form factors make it it possible to determine $|V_{cb}|$. In HQET it is the relative velocity of the initial and final state mesons that matters: at the point of zero recoil, when $\Delta\vec{v} = 0$ (corresponding to $w \equiv v_\mu v^\mu = 1$), the initial and final state "brown mucks" are identical. The Isgur-Wise function $\xi(w)$ characterizes the overlap of the initial and final state mesons' light quark wavefunctions. In the limit of exact heavy quark symmetry, $\xi(1) = 1$, and all the semileptonic form factors can be related to $\xi(w)$. Violations of heavy quark symmetry would spoil the various relations among the form factors such as $R_2 = R_1 = 1$.

Recent results on the $B \to D\ell\nu$ form factors, summarized in Table 7, come from CLEO[13] and ALEPH[14]. The CLEO measurement is based on $144.3 \pm 18.9$ $D^0\ell\nu$ events and $322.8 \pm 30.3$ $D^+\ell\nu$ events, while the ALEPH result is determined from 261 $D^+\ell\nu$ decays. The dominant background comes from $B \to D^*\ell\nu$ feed-down. Both groups fit $f_+(q^2)$ as a linear function of $w$ and extract $\hat{\rho}^2_D$, the $q^2$ slope: $f_+(q^2) = f_+(w=1)\left[1 - \hat{\rho}^2_D\,(w-1)\right]$.

| | $\hat{\rho}^2_D$ |
|---|---|
| CLEO[13] | $0.59 \pm 0.22 \pm 0.12$ |
| ALEPH[14] | $-0.05 \pm 0.53 \pm 0.38$ |
| average | $0.51 \pm 0.23$ |

Table 7: $B \to D\ell\nu$ form factors

Groups reporting measurements of the $B \to D^*\ell\nu$ form factors include CLEO[15], ARGUS[27], ALEPH[14], DELPHI[16], and OPAL[17]. Some are presented as the result of a simultaneous fit to the three parameters $R_1$, $R_2$, and $\rho^2_{A_1}$ while others fix $R_1 = R_2 = 1$ and fit for an effective slope $\hat{\rho}^2$. There are subtleties in comparing results for $\rho^2_{A_1}$ *and* $\hat{\rho}^2$: since the CLEO and ARGUS acceptances differ from the acceptances of the LEP experiments, the

impact of using incorrect values of $R_1$ and $R_2$ will shift the extracted values of $\hat{\rho}^2$ away from the true value of $\rho^2_{A_1}$ *differently* for each experiment.

The best measurements of $|V_{cb}|$ are likely to come from $B \to D^* \ell\nu$ measurements, extrapolated to $w = 1$. A CLEO determination[15] of $R_1$, $R_2$, and $\rho^2_{A_1}$ (based on $779 \pm 42$ $\bar{B}^0 \to D*^+ \ell^- \bar{\nu}$ $(+CC)$ and $417 \pm 33$ $B^- \to D*^0 \ell^- \bar{\nu}$ $(+CC)$), as well as a few theory predictions[40–42], are shown in Table 8. Measurements of $\hat{\rho}^2$, which fix $R_1 = R_2 = 1$ and fit for $d\Gamma/dw$, have come from several experiments, and are summarized in Table 9. Agreement among the experiments is less than stellar, with $\chi^2/D.O.F. \sim 3$. However, the extrapolation to large $q^2$ (most important for the determination of $|V_{cb}|$, to be discussed below) is in better agreement.

| | $R_1$ | $R_2$ | $\hat{\rho}^2_{A_1}$ |
|---|---|---|---|
| CLEO measurement[15] | $1.24 \pm 0.26 \pm 0.12$ | $0.72 \pm 0.18 \pm 0.07$ | $0.92 \pm 0.12 \pm 0.06$ |
| Neubert[42] | 1.3 | 0.8 | |
| Close & Wambach[40] | 1.1 | 0.9 | |
| ISGW2[41] | 1.3 | 1.0 | |

Table 8: The $B \to D^* \ell\nu$ form factors $R_1$, $R_2$, and $\hat{\rho}^2_{A_1}$

| | $\hat{\rho}^2$ |
|---|---|
| CLEO[15] | $0.84 \pm 0.13 \pm 0.08$ |
| ARGUS[27] | $1.17 \pm 0.22 \pm 0.06$ |
| ALEPH [14] | $0.31 \pm 0.17 \pm 0.08$ |
| DELPHI[16] | $0.75 \pm 0.17 \pm 0.10$ |
| OPAL[17] | $0.42 \pm 0.17$ |
| average | $0.68 \pm 0.08$ |

Table 9: $B \to D^* \ell\nu$ form factors

## $V_{cb}$ measurements

The $3 \times 3$ CKM matrix relates the "basis quarks" of the strong and weak interactions. Since the matrix is unitary (assuming 3 generations), $\sum_i V_{ij} V^*_{ik} = \delta_{jk}$. Of particular interest is the triangle relationship $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$: if the Standard Model is the source of CP violation, then $ImV_{ud}V^*_{ub} = ImV^*_{td}V_{tb} \neq 0$. The matrix elements are known with varying degrees of accuracy, ranging from $|V_{ud}| = 0.9736 \pm 0.0010$ (known to 0.1% of itself) to $|V_{ts}| = (3.8 \pm 1.5) \times 10^{-3}$ (known to 40%).

Methods for determining $|V_{cb}|$ include measurements of the partial rate for the inclusive decays $\Gamma(B \to c\ell\nu)$ and determination of the exclusive decay rates $\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})$. The inclusive partial rate is

$$\Gamma(B \to c\ell\nu) = \frac{G_F^2 m_b^5}{192\pi^3} f\left(\frac{m_c}{m_b}\right) |V_{cb}|^2 \eta_0$$

where $f(m_c/m_b) \sim 0.5$ is a phase space factor and $\eta_0 \sim 0.9$ is a (calculable) QCD term. Measurements of inclusive partial rates provide the best statistical precision, but suffer

from model dependence associated with the relative fractions of different species of $B's$ assumed by the analyses. There is a certain amount of disagreement between the LEP and CLEO results, perhaps arising from this. $|V_{cb}|$ measurements derived from $\Gamma(\bar{B} \to D^* \ell \bar{\nu})$ profit greatly from the use of HQET to reduce the model dependences. Experiments measure $d\Gamma/dq^2$ and extrapolate to the point of zero-recoil for the $D^*$. Thanks to Luke's theorem, corrections to the form factors at maximum $q^2$ only enter to second order in $\Lambda_{QCD}/m_Q$.

Shown in Table 10 is a summary of recent results on the product of $|V_{cb}|$ with the form factor $F(w = 1)$ from exclusive $\bar{B} \to D^* \ell \bar{\nu}$. Note that the agreement among the various experiments is considerably better than for the $\hat{\rho}^2$ values shown in Table 9. The $\bar{B} \to D \ell \bar{\nu}$ branching ratio is less than half that for $\bar{B} \to D^* \ell \bar{\nu}$, and the absence of the soft pion associated with the decay of a $D^*$ makes for a different set of analysis issues in a $D \ell \bar{\nu}$ measurement. It is expected[28] that $F_D(1)/F(1) = 1.08 \pm 0.06$; this may be used to interpret the CLEO[13] and ALEPH[14] results for $|F_D(1)V_{cb}|$ displayed in Table 11. The values obtained are consistent with those obtained from $\bar{B} \to D^* \ell \bar{\nu}$.

| | $\|F(1)V_{cb}\| \times 10^3$ | $N_{events}$ |
|---|---|---|
| CLEO[26] | $35.1 \pm 1.9 \pm 1.8 \pm 0.8$ | 678 |
| ARGUS[27] | $44.5 \pm 5 \pm 3$ | 235 |
| ALEPH[14] | $31.9 \pm 1.8 \pm 1.9$ | 579 |
| DELPHI[16] | $35.4 \pm 1.9 \pm 2.4$ | 445 |
| OPAL[17] | $32.8 \pm 1.9 \pm 2.2$ | 502 |
| average | $34.3 \pm 1.4$ | |
| $\langle \|V_{cb}\| \rangle$ *for* $F(1) = .91$ | $(37.7 \pm 1.5) \times 10^{-3}$ | |

Table 10: $|F(1)V_{cb}|$ determinations from $\Gamma(\bar{B} \to D^* \ell \bar{\nu})$

## Tests of factorization

It is possible to relate some bottom and charm two-body hadronic decay amplitudes to semileptonic amplitudes and meson decay constants. In "class I" decay processes (for example, $\bar{B}^0 \to D^+ \pi^-$) the $q, \bar{q}$ produced by a $W^\pm$ combine to form one of the final state mesons. In class II processes (for example, $B^- \to K^- \psi$), each quark from the $W$ combines with a quark line from the parent particle to form the final state mesons. Class III decays (such as $B^- \to D^0 \pi^-$) involve both types of amplitudes. Many tests of this factorization description, comparing relative rates for different processes, are possible. One paper[18] presents 172 different partial decay rates in terms of the class I and class II amplitudes $A_1$ and $A_2$; another[19] lists 42 different $B$ decay modes.

A recent CLEO[20] factorization test involved comparing the B decay rates into $D\pi$, $D^*\pi$, $D\rho$, $D^*\rho$, $Da_1$, and $D^*a_1$. Using the CDDFGN[32] predictions for the decay amplitudes, CLEO determines the amplitude ratio $A_2/A_1 = +0.232 \pm 0.037 \pm 0.022 \pm 0.018$, demonstrating *constructive* interference between the class I and class II amplitudes. If the BSWII[33] predictions are used instead, CLEO obtains $A_2/A_1 = +0.2642 \pm 0.039 \pm 0.025 \pm 0.019$. All is not rosy: this constructive interference would imply a shorter lifetime for charged $B$ mesons than for neutral $B$'s. However, instead of the expected 0.8 lifetime ratio, the LEP electroweak working group finds $\tau_{B^-}/\tau_{\bar{B}^0} = 1.06 \pm 0.04$. It seems that factorization does

| | $\lvert F_D(1)V_{cb}\rvert \times 10^3$ | $N_{events}$ |
|---|---|---|
| CLEO[13] | $33.7 \pm 4.4 \pm 4.8 \pm^{5.3}_{1.2}$ | 467 |
| ALEPH[14] | $27.8 \pm 6.8 \pm 6.5$ | 261 |
| average | $31.1 \pm 6.3$ | |

Table 11: $|F_D(1)V_{cb}|$ determinations from $\Gamma(\bar{B} \to D\ell\bar{\nu})$

not apply to all B decays. Note that the ratio of the D meson lifetimes $\tau_{D^+}/\tau_{D^0} \sim 2.5$ results from destructive interference: $A_2/A_1 = -0.45 \pm 0.05$.

## Charm counting

There is a relationship[22,30] between the average number of charm particles, $n_C$, produced in $B$ decay and the $B$ semileptonic decay branching ratio. Since $B_{SL} \approx \Gamma(b \to c\ell\nu)/(\Gamma_{SL} + \Gamma_{had})$, anything that increases the hadronic partial decay rate will tend to decrease the semileptonic branching ratio. The CLEO[24] and LEP electroweak working group values for the semileptonic branching fraction are $(10.49 \pm 0.17 \pm 0.43)\%$ and $(11.16 \pm 0.20)\%$ respectively; since data at the $Z$ and $\Upsilon(4S)$ contain different mixes of $B$'s, a small difference in the two values is not surprising. With the semileptonic fractions in this range, one expects an average of $\sim 1.2$ charm particles per $B$ decay. The experimental results, shown in Table 12, favor a smaller value for $n_C$.

| decay mode | CLEO | ALEPH | OPAL | DELPHI[29] |
|---|---|---|---|---|
| $D^0X \times 100$ | $63.6 \pm 3.0$ | $60.5 \pm 3.6$ | $53.5 \pm 4.1$ | |
| $D^+X \times 100$ | $23.5 \pm 2.7$ | $23.4 \pm 1.6$ | $18.8 \pm 2.0$ | |
| $D_S^+X \times 100$ | $12.1 \pm 1.7$ | $18.3 \pm 5.0$ | $20.8 \pm 3.0$ | |
| $\Lambda_S^+X \times 100$ | $3.9 \pm 2.0$ | $11.0 \pm 2.1$ | $12.5 \pm 2.6$ | |
| $\Xi_C X \times 100$ | $2.0 \pm 1.0$ | estimated | estimated | |
| $(c\bar{c}) \times 100$ | $5.4 \pm 0.7$ | estimated | estimated | |
| $n_C$ | $1.10 \pm 0.05$ | $1.20 \pm 0.07$ | $1.13 \pm 0.06$ | $1.16 \pm 4.5$ |

Table 12: Contributions to $n_C$ in $B$ decay

Could "upper vertex" charm[23] be an explanation? It was recently realized that diagrams in which the $q\bar{q}$ produced directly by the $W^\pm$ included a $c$ (and/or a $\bar{c}$) might play a significant role. Experiment Monte Carlo simulations had failed to account for this source of charm, and further investigation showed that "wrong-sign" charm makes a non-negligible contribution to the total amount of charm. For example, CLEO finds[31] that $\mathrm{B}\,(B \to D\,X) = 0.081 \pm 0.026$ and $\mathrm{B}\left(B \to D_S^+\,X\right) = 0.10 \pm 0.027$ while DELPHI[29] measures $\mathrm{B}\,(B(\text{meson, baryon mix}) \to X_c + X_{\bar{c}} + X) = (16.3 \pm 4.6)\,\%$. However, the experimenters are convinced that their simulations were inaccurate in the relative mix of charm, but not in the overall rate of charm production, so the discrepancy cannot be explained by improper modeling of upper vertex charm.

1. Bai, J.Z. *et al.* (BES), SLAC-PUB-7147 (1996).
2. Gibaut, D. *et al.* (CLEO), CLEO CONF 95-22 (1995).

3. Parodi, F. *et al.* (DELPHI), DELPHI 97-105 CONF 87 (1997).
4. Acciarri, M. *et al.* (L3), Phys. Lett. **B396**, 327 (1997).
5. Artuso, M. *et al.* (CLEO), Phys. Rev. Lett. **75**, 785 (1995).
6. ALEPH collaboration, ALEPH PA10-019 (1996).
7. Bean, A. *et al.* (CLEO), CLNS 93/1249 (1993).
8. Frabetti, P.L. *et al.* (E687), Phys. Lett. **B364**, 127 (1995).
9. Aitala, E.M. *et al.*, Phys. Lett. **B397**, 325 (1997).
10. Frabetti, P.L. *et al.* (E687), Phys. Lett. **B307**, 262 (1993).
11. Frabetti, P.L. *et al.* (E687), Phys. Lett. **B328**, 187 (1994).
12. Brandenburg, G. *et al.* (CLEO), Phys. Rev. Lett. **75**, 3804 (1995).
13. Athanas, M. *et al.* (CLEO), Phys. Rev. Lett. **79**, 2208 (1997).
14. Buskulic, D. *et al.* (ALEPH), Phys. Lett. **B395**, 373 (1997).
15. Anastassov, A. *et al.* (CLEO), CLEO CONF 96-8 (1996).
16. Abreu, P. *et al.* (DELPHI), Z. Phys. **C71**, 539 (1996).
17. Ackerstaff, K. *et al.* (OPAL), Phys. Lett. **B395**, 128 (1997).
18. Bauer, M., Stech, B., and Wirbel, M., Z. Phys. **C34**, 103 (1987).
19. Neubert, M. and Stech, B., CERN-TH-97-099 (1997).
20. Barish, B. *et al.* (CLEO), CLEO CONF 97-01 (1997).
21. Jessop, C.P. *et al.* (CLEO), CLNS 96/1455 (1996).
22. Neubert, M. and Sachradja, C.T., Nucl. Phys. **B483**, 339 (1997).
23. Buchalla, G., Dunietz, I., and Yamamoto, H., Phys. Lett. **B364**, 188 (1995). 24. Barish, B. *et al.* (CLEO), CLNS 95/1362 (1995).
25. Rosner, J, EFI-96-46 1996).
26. Barish, B. *et al.* (CLEO), Phys. Rev. **D51**, 1014 (1995).
27. Albrecht, H. *et al.* (ARGUS), Z. Phys. **C57**, 533 (1993).
28. Ligeti, Z., Yosef Nir, Y., and Neubert, M., Ligeti and Nir, Phys. Rev. **D49**, 1302 (1994).
29. Battaglia, M. *et al.* (DELPHI), DELPHI 97-80 CONF 66 (1997).
30. Bigi, I. *et al.*, Phys. Lett. **B323**, 408 (1994).
31. Glenn, S. *et al.* (CLEO), CLEO CONF 97-27 (1997).
32. Deandrea, A. *et al.* (CDDFGN), Phys. Lett. **B318**, 549 (1993).
33. Neubert, M. *et al.* (BSWII), in *Heavy Flavours*, A.J. Buras and H. Lindner, eds., World Scientific, Singapore (1992).
34. Bai, J.Z. *et al.* (BES), Phys. Rev. Lett. **74**, 4599 (1995).
35. Aoki, S. *et al.* (WA75) Progr. Theor. Phys. **89**, 131 (1993).
36. Kodama, K. *et al.* (E653) Phys. Lett. **B382**, (1996).
37. Allton, C.R. *et al.* (APE), Phys. Lett. **B345**, 513 (1995).
38. Abada, As. *et al.* (ELC), Nucl. Phys. B **416**, 675 (1994).
39. Bowler, K.C. *et al.* (UKQCD), Phys. Rev. D **51**, 4905 (1995).
40. Close, F.E., and Wambach, A., Phys. Lett. **B348**, 207 (1995).
41. Isgur, N. *et al.* (ISGW2), Phys. Rev. D **52**, 2783 (1995).
42. Neubert, M. Phys. Reports **245**, 259 (1994).