PRODUCTION AND DECAY OF b-FLAVORED HADRONS

Written March 1998 by K. Honscheid (Ohio State University, Columbus).

In 1997 we celebrated the 20th anniversary of the discovery of the b quark. What started out as a bump in the dimuon invariant mass spectrum has turned into the exciting field of heavy flavor physics. Weak decays of heavy quarks provide access to fundamental parameters of the Standard Model, in particular the weak mixing angles of the Cabibbo-Kobayashi-Maskawa matrix. There is great hope that experiments with B mesons may lead to the first precise determination of the fourth CKM parameter, the complex phase. While the underlying decay of the heavy quark is governed by the weak interaction, it is the strong force that is responsible for the formation of the hadrons that are observed by experimenters. Although this complicates the extraction of the Standard Model parameters from the experimental data it also means that decays of B mesons provide an important laboratory to test our understanding of the strong interaction.

New results that were added to this edition fall into two categories. Arguably the most exciting development since the last edition of this review is the progress in b-quark decays beyond the tree level. Gluonic penguin decays such as $B \to K^- \pi^+$ have been measured for the first time providing us with new opportunities to search for physics beyond the Standard Model and/or to probe the phase structure of the CKM matrix.

At tree level, *i.e.* for $b \to c$ transitions, the CLEO collaboration used a sample of more than 6 million B decays to update branching fractions for many exclusive hadronic decay channels. New results on semileptonic decays have been reported by CLEO and the LEP collaborations. Lifetime measurements improved steadily and now have reached a precision of a few percent.

Heavy flavor physics is a very dynamic field and in this brief review it is impossible to do justice to all recent theoretical and experimental developments. I will highlight a few new results but otherwise refer the interested reader to several excellent reviews [1–4].

Production and spectroscopy: Elementary particles are characterized by their masses, lifetimes and internal quantum numbers. The bound states with a b quark and a $\overline{u}$ or $\overline{d}$ antiquark are referred to as the B_d ($\overline{B^0}$) and the B_u (B^-) mesons, respectively. The first excitation is called the B^* meson. B^{**} is the generic name for the four orbitally excited ($L = 1$) B-meson states that correspond to the P-wave mesons in the charm system, D^{**}. Mesons containing an s or a c quark are denoted B_s and B_c, respectively.

Experimental studies of b decay are performed at the $\Upsilon(4S)$ resonance near production threshold as well as at higher energies in proton-antiproton collisions and Z decays. Most new results from CLEO are based on a sample of $\approx 3.1 \times 10^6$ $B\overline{B}$ events. At the Tevatron, CDF and DØ have collected 100 pb^{-1} of data. Operating at the Z resonance each of the four LEP collaborations recorded slightly under a million $b\bar{b}$ events while the SLD experiment collected about 0.2 million hadronic Z decays.

For quantitative studies of B decays the initial composition of the data sample must be known. The $\Upsilon(4S)$ resonance decays only to $B^0\overline{B}^0$ and B^+B^- pairs, while at high-energy collider experiments heavier states such as B_s or B_c mesons and b-flavored baryons are produced as well. The current experimental limit for non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is less than 4% at the 95% confidence level [5]. CLEO has measured the ratio of charged to neutral $\Upsilon(4S)$ decays using semileptonic B decays and found [6]

$$\frac{f_+}{f_0} = \frac{\mathcal{B}(\Upsilon(4S) \to B^+B^-)}{\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)} = 1.13 \pm 0.14 \pm 0.13 \pm 0.06 \quad (1)$$

where the last error is due to the uncertainties in the ratio of B^0 and B^+ lifetimes. Assuming isospin symmetry an independent value can be obtained from $\mathcal{B}(B^- \to J/\psi K^{(*)-})$ and $\mathcal{B}(\overline{B}^0 \to J/\psi \bar{K}^{(*)0})$ [7]:

$$\frac{f_+}{f_0} = 1.11 \pm 0.17 \ . \quad (2)$$

This is consistent with equal production of B^+B^- and $B^0\overline{B}^0$ pairs and unless explicitly stated otherwise we will assume $f_+/f_0 = 1$. This assumption is further supported by the near equality of the B^+ and B^0 masses.

At high-energy collider experiments b quarks hadronize as $\bar{B}^0$, B^-, $\bar{B}^0_s$, and B^-_c mesons or as baryons containing b quarks. The b-hadron sample composition is not very precisely known although over the last few years significant improvements have been achieved, in particular thanks to B^0 oscillation measurements. The fractions f_{B^0}, f_{B^+}, f_{B_s}, and f_{Λ_b} of B^0, B^+, B^0_s, and b baryons in an unbiased sample of weakly decaying b hadrons produced at the Z resonance are shown in Table 1. They have been estimated by the LEP B oscillations working group [8] using the assumptions $f_{B^0} = f_{B^+}$ and $f_{B^0} + f_{B^+} + f_{B_s} + f_{\Lambda_b} = 1$ (the B^+_c fraction is neglected). The procedure is summarized below.

An estimate of f_{B_s} is obtained from the measurements of the product branching fraction $f_{B_s} \times \mathcal{B}(B_s \to D^-_s \ell^+ \nu_\ell X)$. Under the assumption of equal semileptonic partial widths for b-flavored hadrons, results from the $\Upsilon(4S)$ experiments and the b-hadron lifetimes (Table 2) are combined to obtain an estimate for $\mathcal{B}(B_s \to D^-_s \ell \nu_\ell X)$. Together these are used to extract $f_{B_s} = (12.0^{+4.5}_{-3.4})\%$. A similar procedure is followed to obtain $f_{\Lambda_b} = (10.1^{+3.9}_{-3.1})\%$ from measurements of $f_{\Lambda_b} \times \mathcal{B}(\Lambda_b \to \Lambda^+_c \ell^- \overline{\nu}_\ell X)$. A statistically independent estimate $f_{B_s} = (10.1^{+2.0}_{-1.9})\%$ is then derived from measurements of B^0 oscillations. This is done using measurements of the mixing parameters $\chi_d = (1/2) \cdot x^2_d/(1 + x^2_d)$, in which $x_d = \Delta m_d \tau_{B^0}$, and $\overline{\chi} = f'_{B_s}\chi_s + f'_{B^0}\chi_d$. Here f'_{B_s} and f'_{B^0} are the fractions of B^0_s and B^0 mesons among semileptonic b decays. The dependence on the lifetimes is taken into account and $\chi_s = 1/2$ is assumed. This estimation is performed simultaneously with the Δm_d averaging described in the mixing section below. An average of the two estimates of f_{B_s}, taking the correlated systematic effects into account, yields $f_{B_s} = (10.5^{+1.8}_{-1.7})\%$ and hence the fractions of Table 1.

Table 1: Fractions of weakly decaying b-hadron species in $Z \to b\overline{b}$ decay.

b hadron	Fraction [%]
B^-	$39.7^{+1.8}_{-2.2}$
$\bar{B}^0$	$39.7^{+1.8}_{-2.2}$
$\bar{B}^0_s$	$10.5^{+1.8}_{-1.7}$
b baryons	$10.1^{+3.9}_{-3.1}$

To date, the existence of four b-flavored mesons (B^-, $\overline{B}^0$, B^*, B_s) as well as the Λ_b baryon has been established. Using exclusive hadronic decays such as $B^0_s \to J/\psi\phi$ and $\Lambda_b \to J/\psi\Lambda$ the masses of these states are now known with a precision of a few MeV. The current world averages of the B_s and the Λ_b mass are 5369.6 ± 2.4 MeV/c^2 and 5624 ± 9 MeV/c^2, respectively.

The B_c is the last weakly decaying bottom meson to be observed. Potential models predict its mass in the range 6.2–6.3 GeV/c^2. At the 1998 La Thuile conference CDF presented an analysis providing clear evidence for semileptonic $B_c \to J/\psi\ell X$ decays with $20.4^{+6.2}_{-5.5}$ observed events [13]. CDF reconstructs a B_c mass of $6.4 \pm 0.39\pm\ 0.13$ GeV/c^2 and a B_c lifetime of $0.46^{+0.18}_{-0.16} \pm 0.03$ ps.

First indications of Σ_b and Ξ_b production have been presented by the LEP collaborations [14]. DELPHI has measured the $\Sigma^*_b - \Sigma_b$ hyperfine splitting to 56 ± 16 MeV [15].

Excited B-mesons states have been observed by CLEO, CUSB, and LEP. Evidence for B^{**} production has been presented by ALEPH, OPAL, and DELPHI [3]. Inclusively reconstructing a bottom hadron candidate combined with a charged pion from the primary vertex they see the B^{**} as broad resonance in the $M(B\pi)$–$M(B)$ mass distribution. The LEP experiments have also provided preliminary evidence for excited B^{**}_s states and DELPHI [16] has reported a possible observation of the B', the first radial excitation in the B meson system.

Lifetimes: In the naive spectator model the heavy quark can decay only via the external spectator mechanism and thus the lifetimes of all mesons and baryons containing b quarks would be equal. Nonspectator effects such as the interference between contributing amplitudes modify this simple picture and give rise to a lifetime hierarchy for b-flavored hadrons similar to the one in the charm sector. However, since the lifetime differences are expected to scale as $1/m_Q^2$, where m_Q is the mass of the heavy quark, the variation in the b system should be significantly smaller, of order 10% or less [17]. For the b system we expect

$$\tau(B^-) \;\geq\; \tau(\overline{B}^0) \;\approx\; \tau(B_s) \;>\; \tau(\Lambda_b^0)\ . \tag{3}$$

Measurements of lifetimes for the various b-flavored hadrons thus provide a means to determine the importance of non-spectator mechanisms in the b sector. Precise lifetimes are important for the determination of V_{cb}. They also enter in $B\overline{B}$ mixing measurements.

Over the past years the field has matured and advanced algorithms based on impact parameter or decay length measurements exploit the potential of silicon vertex detectors. However, in order to reach the precision necessary to test theoretical predictions, the results from different experiments need to be averaged. This is a challenging task that requires detailed knowledge of common systematic uncertainties and correlations between the results from different experiments. The average lifetimes for b-flavored hadrons given in this edition have been determined by the LEP B Lifetimes Working Group [19]. The papers used in this calculation are listed in the appropriate sections. A detailed description of the procedures and the treatment of correlated and uncorrelated errors can be found in [20]. The new world average b-hadron lifetimes are summarized in Table 2. Lifetime measurements have reached a precision that the average b-hadron lifetime result becomes sensitive to the composition of the data sample. The result listed in Table 2 takes into account correlations between different experiments and analysis techniques but does not correct for differences due to different admixtures of b-flavored hadrons. In order to estimate the size of this effect the available results have been divided into three sets. LEP measurements based on the identification of a lepton from the b decay yield $\tau_{b\ \mathrm{hadron}} = 1.537 \pm 0.020\ \mathrm{ps}^{-1}$ [21–23]. The average b-hadron lifetime based on inclusive secondary vertex techniques is $\tau_{b\ \mathrm{hadron}} = 1.576 \pm 0.016\ \mathrm{ps}^{-1}$ [24–29]. Finally, CDF [30] used ψ mesons to tag the b vertex resulting in $\tau_{b\ \mathrm{hadron}} = 1.533 \pm 0.015^{+0.035}_{-0.031}\ \mathrm{ps}^{-1}$.

Table 2: Summary of inclusive and exclusive b-hadron lifetime measurement.

Particle	Lifetime [ps]
B^0	1.56 ± 0.04
B^+	1.65 ± 0.04
B_s	1.54 ± 0.07
b baryon	1.22 ± 0.05
b hadron	1.564 ± 0.014

For comparison with theory lifetime ratios are preferred. Experimentally we find [19]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.04 \pm 0.04\ ,\quad \frac{\tau_{B_s}}{\tau_{B^0}} = 0.99 \pm 0.05\ ,\quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.79 \pm 0.06 \tag{4}$$

while theory makes the following predictions [1]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1 + 0.05\left(\frac{f_B}{200\ \mathrm{MeV}}\right)^2\ ,\quad \frac{\tau_{B_s}}{\tau_{B^0}} = 1 \pm 0.01\ ,\quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.9\ . \tag{5}$$

In conclusion, the pattern of measured B-mesons lifetimes follows the theoretical expectations and non-spectator effects are observed to be small. However, the Λ_b-baryon lifetime is unexpectedly short. As has been noted by several authors, the observed value of the Λ_b lifetime is quite difficult to accommodate theoretically [31–33]. This apparent breakdown of the heavy-quark expansion for inclusive, non-leptonic B decays could be caused by violations of local quark-hadron duality. Neubert, however, argues that this conclusion is premature because a reliable field-theoretical calculation is still lacking. Exploring a reasonable parameter space for the unknown hadronic matrix elements he demonstrated that within the experimental errors theory can accommodate the measured lifetime ratios [1].

$B\overline{B}$ mixing: In production processes involving the strong or the electromagnetic interaction neutral B and $\overline{B}$ mesons can be produced. These flavor eigenstates are not eigenstates of the weak interaction which is responsible for the decay of neutral mesons containing b quarks. This feature and the small difference between the masses and/or lifetimes of the weak interaction eigenstates give rise to the phenomenon of B–$\overline{B}$ mixing. The formalism which describes B-meson mixing closely follows that used to describe K^0–$\overline{K}^0$ mixing, although the time scale characteristic of B^0–$\overline{B}^0$ oscillations is much shorter [34].

The ALEPH, DELPHI, L3, OPAL, SLD, and CDF experiments have performed explicit measurements of Prob($B^0 \to \overline{B}^0$) as a function of proper time to extract the oscillation parameter $\Delta m_d = x_d \Gamma_d$ [3]. The flavor of the final state b quark is tagged using the charge of a lepton, a fully or partially reconstructed charmed meson, or a charged kaon, from $b \to \ell^-$, $b \to c$ or $b \to c \to s$ decays respectively. For fully inclusive analyses, final state tagging techniques include jet charge and charge dipole methods. The initial state flavor is either tagged directly (same-side tag) or indirectly by tagging the flavor of the other b hadron produced in the event (opposite-side tag). Same-side tagging can be performed with a charged hadron produced in association with the B meson (possibly through a B^{**} state), and opposite-side tagging can be performed with a lepton or a kaon from the decay of the other b hadron. Jet charge techniques have also been used on both sides. If the B meson is produced with polarized beams, its polar angle with respect to the incoming beam axis can also be used to construct an initial state tag.

The LEP B oscillations working group has combined all published measurements of Δm_d to obtain an average of 0.470 ± 0.019 ps^{-1} [8]. The averaging procedure takes into account all correlated uncertainties as well as the latest knowledge on the b-hadron production fractions (Table 1), lifetimes (Table 2) and time-integrated parameters. Including the data from the time-integrated measurements performed by ARGUS and CLEO at the $\Upsilon(4S)$ resonance yields a combined result of $\Delta m_d = 0.464 \pm 0.018$ ps^{-1}. Averaging time-dependent results from LEP and CDF and time-integrated measurements from CLEO and ARGUS the time-integrated mixing parameter χ_d is determined to 0.172 ± 0.010. As stated earlier, Δm_d and the

b-hadron fractions are determined simultaneously, providing a self-consistent set of results.

The measurement of the oscillation parameter $\Delta m_s = x_s\Gamma_s$ for the B_s^0 meson combined with the results from the B^0–$\overline{B}^0$ oscillations allows the determination of the ratio of the CKM matrix elements $|V_{td}|^2/|V_{ts}|^2$ with significantly reduced theoretical uncertainties. For large values, as expected for the B_s^0 meson, time-integrated measurements of B_s^0 mixing become insensitive to Δm_s and one must make time-dependent measurements in order to extract this parameter. The observation of the rapid oscillation rate of the B_s^0 meson is an experimental challenge that is still to be met. The ALEPH, DELPHI, and OPAL experiments have provided lower limits on Δm_s [3]. The most sensitive analyses use inclusive leptons or fully reconstructed D_s^- mesons. All published data have been combined by the LEP B oscillations working group to yield the limit $\Delta m_s > 9.1\ \mathrm{ps}^{-1}$ at 95% C.L. [8].

For the B_s meson, the quantity $\Delta\Gamma$ may be large enough to be observable [18]. Parton model calculations [9] and calculations with exclusive final states [10] suggest that the width difference may be 10–20%. This lifetime difference could be determined experimentally by using decays to final states with different CP. For example, a measurement of a difference in the lifetimes between $\overline{B}_s^0 \to J/\psi K_s$ and $\overline{B}_s^0 \to D_s^- \ell^+ \nu_\ell$ would yield $\Delta\Gamma/\Gamma^2$. It has also been suggested that such measurements could be used to constrain $|V_{ts}/V_{td}|^2$ if parton model calculations are reliable [11].

Semileptonic B decays: Measurements of semileptonic B decays are important to determine the weak couplings $|V_{cb}|$ and $|V_{ub}|$. In addition, these decays can be used to probe the dynamics of heavy quark decay. The leptonic current can be calculated exactly while corrections due to the strong interaction are restricted to the $b \to c$ and $b \to u$ vertices, respectively.

Experimentally, semileptonic decays have the advantage of large branching ratios and the characteristic signature of the energetic charged lepton. The neutrino, however, escapes undetected so a full reconstruction of the decaying B meson is impossible. Various techniques which take advantage of production at threshold or the hermiticity of the detector have been developed by the ARGUS, CLEO, and LEP experiments to overcome this difficulty.

Three different approaches have been used to measure the inclusive semileptonic rate $B \to X\ell\nu_\ell$. These are measurements of the inclusive single lepton momentum spectrum, measurements of dilepton events using charge and angular correlations, and measurements of the separate B^- and $\overline{B}^0$ branching ratios by using events which contain a lepton and a reconstructed B meson. The dilepton method has the least model-dependency and the current averages based on this method are listed in Table 3 [2]. Differences in $\mathcal{B}_{sl}$ measured at the $\Upsilon(4S)$ and the Z are expected due to the different admixture of b-flavored hadrons. Given the short Λ_b lifetime, however, the LEP value should be lower than the $\Upsilon(4S)$ result. While the experimental errors are still too large to draw any conclusions a potential systematic effect in the LEP results has been pointed out by Dunietz [12]. He noted that the LEP analyses have not yet been corrected for the recently observed production of $\overline{D}$ mesons in $\overline{B}$ decay.

A few new results on exclusive semileptonic B decays have been reported. The current world averages are listed in Table 3. It is interesting to compare the inclusive semileptonic branching fraction to the sum of branching fractions for exclusive modes. At the 2–3 σ level the exclusive modes saturate the inclusive rate leaving little room for extra contributions.

Dynamics of semileptonic B decay: Since leptons are not sensitive to the strong interaction, the amplitude for a semileptonic B decay can be factorized into two parts, a leptonic and a hadronic current. The leptonic factor can be calculated exactly while the hadronic part is parameterized by form factors. A simple example is the transition $B \to D\ell\nu_\ell$. The differential decay rate in this case is given by

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cb}^2|P_D^3 f_+^2(q^2) \tag{6}$$

Table 3: Inclusive and exclusive semileptonic branching fractions of B mesons. $\mathcal{B}(\overline{B} \to X_u \ell^- \overline{\nu}_\ell) = 0.15 \pm 0.1\%$ has been included in the sum of the exclusive branching fractions.

Mode		Branching fraction [%]
$\overline{B} \to X\ell^-\overline{\nu}_\ell(\Upsilon(4S))$		10.18 ± 0.39
$b \to X\ell^-\overline{\nu}_\ell(Z)$		10.95 ± 0.32
$\overline{B} \to D\ell^-\overline{\nu}_\ell$		1.95 ± 0.27
$\overline{B} \to D^*\ell^-\overline{\nu}_\ell$		5.05 ± 0.25
$\overline{B} \to D^{(*)}\pi\ell^-\overline{\nu}_\ell$		2.3 ± 0.44
with $\overline{B} \to D_1^0(2420)\ell^-\overline{\nu}_\ell$	0.65 ± 0.11	
$\overline{B} \to D_2^{*0}(2460)\ell^-\overline{\nu}_\ell$	< 0.8 90% CL	
$\Sigma\mathcal{B}_{\text{exclusive}}$		9.45 ± 0.58

where q^2 is the mass of the virtual W ($\ell\nu_\ell$) and $f_+(q^2)$ is the single vector form factor which gives the probability that the final state quarks will form a D meson. Since the leptons are very light the corresponding $f_-(q^2)$ form factor can be neglected. For $B \to D^*\ell\nu_\ell$ decays there are three form factors which correspond to the three possible partial waves of the $B \to D^*\widehat{W}$ system (here $\widehat{W}$ is the virtual W boson which becomes the lepton-antineutrino pair). Currently, form factors cannot be predicted by theory and need to be determined experimentally. Over the last years, however, it has been appreciated that there is a symmetry of QCD that is useful in understanding systems containing one heavy quark. This symmetry arises when the quark becomes sufficiently heavy to make its mass irrelevant to the nonperturbative dynamics of the light quarks. This allows the heavy quark degrees of freedom to be treated in isolation from the the light quark degrees of freedom. This is analogous to the canonical treatment of hydrogenic atoms, in which the spin and other properties of the nucleus can be neglected. The behavior and electronic structure of the atom are determined by the light electronic degrees of freedom. Heavy quark effective theory (HQET) was created by Isgur and Wise [35] who define a single universal form factor, $\xi(v \cdot v^{'})$, known as the Isgur-Wise function. In this function v and $v^{'}$ are the four velocities of the initial and final state heavy mesons. The Isgur-Wise function cannot be calculated from first principles but unlike the hadronic form factors mentioned above it is universal. In the heavy quark limit it is the same for all heavy meson to heavy meson transitions and the four form factors parameterizing $B \to D^* \ell \nu_\ell$ and $B \to D \ell \nu_\ell$ decays can be related to this single function ξ.

In this framework the differential semileptonic decay rates as function of $w = v_B \cdot v_{D^{(*)}} = (m_B^2 + m_{D^{(*)}}^2 - q^2)/2m_B m_{D^{(*)}}$ are given by [1]

$$\begin{aligned}\frac{d\Gamma(\overline{B} \to D^* \ell \overline{\nu}_\ell)}{dw} =& \frac{G_F^2 M_B^5}{48\pi^3} r_*^3 (1-r_*)^2 \sqrt{w^2-1}(w+1)^2 \\ & \times \left[1 + \frac{4w}{w+1}\frac{1-2wr_* + r_*^2}{(1-r_*)^2}\right] |V_{cb}|^2 \mathcal{F}^2(w) \\ \frac{d\Gamma(\overline{B} \to D \ell \overline{\nu}_\ell)}{dw} =& \frac{G_F^2 M_B^5}{48\pi^3} r^3 (1+r)^2 (w^2-1)^{3/2} |V_{cb}|^2 \mathcal{G}^2(w) \quad (7)\end{aligned}$$

where $r_{(*)} = M_{D^{(*)}}/M_B$ and q^2 is the invariant momentum transfer. For $m_Q \to \infty$, the two form factors $\mathcal{F}(w)$ and $\mathcal{G}(w)$ coincide with the Isgur-Wise function $\xi(w)$.

Both CLEO [36] and ALEPH [37] have measured the differential decay rate distributions and extracted the ratio $\mathcal{G}(w)/\mathcal{F}(w)$ which is expected to be close to unity. As can be seen from the ALEPH result shown in Fig. 1, the data are compatible with a universal form factor $\xi(w)$

CLEO has also performed a direct measurement of the three form factors that are used to parameterize $B \to D^* \ell \nu_\ell$ decays [38]. These are usually expressed in terms of form factor ratios R_1 and R_2 [39]. At zero recoil, *i.e.* $w = 1$, CLEO finds $R_1 = 1.24 \pm 0.26 \pm 0.12$ and $R_2 = 0.72 \pm 0.18 \pm 0.07$. While the errors are still large, this is in good agreement with a theoretical prediction of $R_1 = 1.3 \pm 0.1$ and $R_2 = 0.8 \pm 0.2$ [1].

Extraction of $|V_{cb}|$: The universal form factor $\xi(w)$ describes the overlap of wavefunctions of the light degrees of freedom in the initial and final heavy meson. At zero recoil, *i.e.* when the two mesons move with the same velocity, the overlap is perfect and the form factor is absolutely normalized, $\xi(1) = 1$. In principle, all that experimentalists have to do to extract

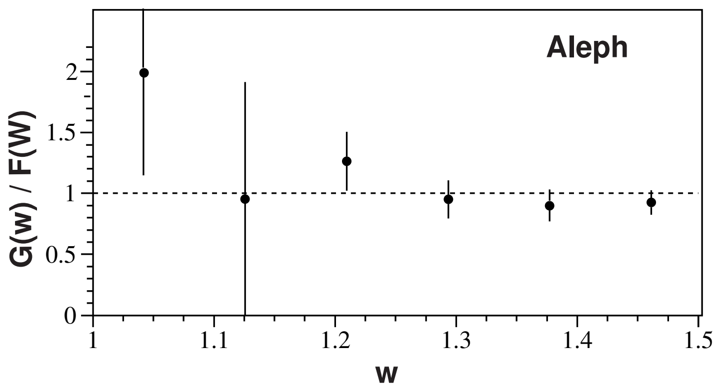

Figure 1: Ratio of the two form factors $\mathcal{G}(w)$ and $\mathcal{F}(w)$ in semileptonic B decay [37].

a model-independent value for $|V_{cb}|$ is to measure $d\Gamma(B \to D^{(*)}\ell\nu_\ell)/dw$ for $w \to 1$. However, in the real world the b and c quarks are not infinitely heavy so corrections to the limiting case have to be calculated. After much theoretical effort, the current results are [1]:

$$\begin{aligned}\mathcal{F}(1) =&0.924 \pm 0.027 \ , \\ \mathcal{G}(1) =&1.00 \pm 0.07 \ . \end{aligned} \tag{8}$$

Furthermore, the shape of the form factor has to be parameterized because at zero recoil the differential decay rate actually vanishes. Experimentally, the decay rate is measured as function of w and then extrapolated to zero recoil using an expansion of form

$$\mathcal{F}(w) = \mathcal{F}(1)\left(1 - \widehat{\rho}^2(w-1)\right) \ . \tag{9}$$

The slope $\widehat{\rho}^2$ of the form factor and $|V_{cb}|$ are correlated. The current world averages for $|V_{cb}|$ and $\widehat{\rho}$ as extracted from exclusive semileptonic B decays have been compiled by Drell [2]. This value of $|V_{cb}|$ is in good agreement with independent determinations of $|V_{cb}|$ from inclusive B decays.

Table 4: Current world averages.

Mode	$\lvert V_{cb}\rvert$	$\widehat{\rho}^2$
$\overline{B} \to D^*\ell^-\overline{\nu}_\ell$	0.0387 ± 0.0031	0.71 ± 0.11
$\overline{B} \to D\ell^-\overline{\nu}_\ell$	0.0394 ± 0.0050	0.66 ± 0.19

Hadronic B decays: In hadronic decays of B mesons the underlying weak transition of the b quark is overshadowed by strong interaction effects caused by the surrounding cloud of light quarks and gluons. While this complicates the extraction of CKM matrix elements from experimental results it also turns the B meson into an ideal laboratory to study our understanding of perturbative and non-perturbative QCD, of hadronization, and of Final State Interaction (FSI) effects.

The precision of the experimental data has steadily improved over the past years. In 1997 CLEO updated most branching fractions for exclusive $B \to (n\pi)^- D^{(*)}$ and $B \to J/\psi K^{(*)}$ transitions. New, tighter limits on color suppressed decays such as $\overline{B} \to D^0\pi^0$ have been presented [41] and a new measurement of the polarization in $B \to J/\psi K^*$ resolved an outstanding discrepancy between theory and experiment [40]. Progress has been made in experimental techniques. Last summer CLEO presented several analyses based on partial reconstruction [48,49]. In this method, D^* mesons are not fully reconstructed but rather tagged by the presence of the characteristic slow pion from the $D^* \to D^0\pi$ decay. This results in substantially increased event yields, *e.g.*, 281 ± 56 $D^{**}(2420)$ candidates have been reconstructed. The preliminary results are

$$\begin{aligned}
\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-) &= (2.81 \pm 0.11 \pm 0.21 \pm 0.05) \times 10^{-3} \\
\mathcal{B}(B^- \to D^{*0}\pi^-) &= (4.81 \pm 0.42 \pm 0.40 \pm 0.21) \times 10^{-3} \\
\mathcal{B}(B^- \to D_1(2420)\pi^-) &= (1.17 \pm 0.24 \pm 0.16 \pm 0.03) \times 10^{-3} \\
\mathcal{B}(B^- \to D_2^*(2460)\pi^-) &= (2.1 \pm 0.8 \pm 0.3 \pm 0.05) \times 10^{-3}. \quad (10)
\end{aligned}$$

The second systematic error reflects the uncertainty in the D^* branching fractions.

Gronau and Wyler [50] first suggested that decays of the type $B \to DK$ can be used to extract the angle γ of the

CKM unitarity triangle, $\gamma \approx \arg(V_{ub})$. The first example of such a Cabibbo suppressed mode has recently been observed by CLEO [51]:

$$\frac{\mathcal{B}(B^- \to D^0 K^-)}{\mathcal{B}(B^- \to D^0 \pi^-)} = 0.055 \pm 0.014 \pm 0.005 \ . \tag{11}$$

Measurements of exclusive hadronic B decays have reached sufficient precision to challenge our understanding of the dynamics of these decays. It has been suggested that in analogy to semileptonic decays, two-body hadronic decays of B mesons can be expressed as the product of two independent hadronic currents, one describing the formation of a charm meson and the other the hadronization of the remaining $\overline{u}d$ (or $\overline{c}s$) system from the virtual W^-. Qualitatively, for a B decay with a large energy release, the $\overline{u}d$ pair, which is produced as a color singlet, travels fast enough to leave the interaction region without influencing the second hadron formed from the c quark and the spectator antiquark. The assumption that the amplitude can be expressed as the product of two hadronic currents is called "factorization" in this paper. By comparing exclusive hadronic B decays to the corresponding semileptonic modes the factorization hypothesis has been experimentally confirmed for decays with large energy release [40]. Note that it is possible that factorization will be a poorer approximation for decays with smaller energy release or larger q^2. For internal spectator decays the validity of the factorization hypothesis is also questionable and requires experimental verification. The naive color transparency argument used in the previous sections is not applicable to decays such as $B \to J/\psi K$, and there is no corresponding semileptonic decay to compare to. For internal spectator decays one can only compare experimental observables to quantities predicted by models based on factorization. Two such quantities are the production ratio

$$\mathcal{R} = \frac{\mathcal{B}(B \to J/\psi K^*)}{\mathcal{B}(B \to J/\psi K)} \tag{12}$$

and the amount of longitudinal polarization Γ_L/Γ in $B \to J/\psi K^*$ decays. Previous experimental results, $\mathcal{R} = 1.68 \pm 0.33$ and $\Gamma_L/\Gamma = 0.78 \pm 0.04$, were inconsistent with all model predictions. The theory had difficulties in simultaneously accommodating a large longitudinal polarization and a large vector-to-pseudoscalar production ratio. Non-factorizable contributions that reduce the transverse amplitude were proposed to remedy the situation. New experimental results, however, make this apparent breakdown of the factorization hypothesis less likely. The CLEO collaboration published new data on $B \to$ charmonium transitions [7]. Their values,

$$\mathcal{R} = 1.45 \pm 0.20 \pm 0.17 \ , \ \Gamma_L/\Gamma = 0.52 \pm 0.07 \pm 0.04 \ , \qquad (13)$$

are now consistent with factorization-based models.

In the decays of charm mesons, the effect of color suppression is obscured by the effects of FSI or reduced by nonfactorizable effects. Because of the larger mass of the b quark, a more consistent pattern of color-suppression is expected in the B system, and current experimental results seem to support that color-suppression is operative in hadronic decays of B mesons. Besides $B \to$ charmonium transitions no other color-suppressed decay has been observed experimentally [41]. The current upper limit on $\mathcal{B}(\overline{B}^0 \to D^0\pi^0)$ is 0.012% at 90% C.L.

By comparing hadronic B^- and $\overline{B}^0$ decays, the relative contributions from external and internal spectator decays have been disentangled. For all decay modes studied the B^- branching ratio was found to be larger than the corresponding $\overline{B}^0$ branching ratio indicating constructive interference between the external and internal spectator amplitudes. In the BSW model [42] the two amplitudes are proportional to effective coefficients, a_1 and a_2, respectively. A least squares fit using the latest branching ratio measurements and a model by Neubert *et al.* [43] gives

$$a_2/a_1 = 0.22 \pm 0.04 \pm 0.06 \ , \qquad (14)$$

where we have ignored uncertainties in the theoretical predictions. The second error is due to the uncertainty in the B-meson production fractions (f_+, f_0) and lifetimes (τ_+, τ_0) that enter into the determination of a_1/a_2 in the combination $(f_+\tau_+/f_0\tau_0)$. As this ratio increases, the value of a_2/a_1 decreases. Varying $(f_+\tau_+/f_0\tau_0)$ in the allowed experimental range ($\pm 20\%$) excludes a negative value of a_2/a_1. Other uncertainties in the magnitude of the decay constants f_D and f_{D^*} as well as in the hadronic form factors can change the magnitude of a_2/a_1 but not its sign.

The magnitude of a_2 determined from this fit to the ratio of B^- and $\overline{B}^0$ branching fractions is consistent with the value of $|a_2|$ determined from the fit to the $B \to J/\psi$ decay modes which only via the color suppressed amplitude. The coefficient a_1 also shows little or no process dependency.

The observation that the coefficients a_1 and a_2 have the same relative sign in B^- decay came as a surprise, since destructive interference was observed in hadronic charm decay. The sign of a_2 disagrees with the theoretical extrapolation from the fit to charm meson decays using the BSW model. It also disagrees with the expectation from the $1/N_c$ rule [44]. The result may be consistent with the expectation of perturbative QCD [45]. B. Stech proposed that the observed interference pattern in charged B and D decay can be understood in terms of the running strong coupling constant α_s [46]. A solution based on PQCD factorization theorems has been suggested by B. Tseng and H.N. Li [47].

Although constructive interference has been observed in all the B^- modes studied so far, these comprise only a small fraction of the total hadronic rate. It is conceivable that higher multiplicity B^- decays demonstrate a very different behaviour.

It is intriguing that $|a_1|$ determined from $B \to D^{(*)}\pi$, $D^{(*)}\rho$ modes agrees well with the value of a_1 extracted from $B \to DD_s$ decays. The observation of color-suppressed decays such as $\overline{B}^0 \to D^0\pi^0$ would give another measure of $|a_2|$ complementary to that obtained from $B \to$ charmonium decays.

In summary, experimental results on exclusive B decay match very nicely with theoretical expectations. Unlike charm the b quark appears to be heavy enough so that corrections due to the strong interaction are small. Factorization and color-suppression are at work. An intriguing pattern of constructive interference in charged B decays has been observed.

Inclusive hadronic decays: Over the last years inclusive B decays have become an area of intensive studies, experimentally as well as theoretically. Since the hadronization process to specific final state mesons is not involved in inclusive calculations the theoretical results and predictions are generally believed to be more reliable.

CLEO and the LEP collaborations presented new measurements of inclusive $b \to c$ transitions that can be used to extract n_c, the number of charm quarks produced per b decay. Naively we expect $n_c = 115\%$ with the additional 15% coming from the decay of the W boson to $\overline{c}s$. This expectation can be verified experimentally by adding all inclusive $b \to c$ branching fractions. Using CLEO and LEP results we can perform the calculation shown in Table 5. Modes with 2 charm quarks in the final state are counted twice. For the unobserved $B \to \eta_c X$ decay we take the experimental upper limit. B_s mesons and b baryons produced at the Z but not at the $\Upsilon(4S)$ cause the increase in D_s and Λ_c production rates seen by LEP. To first order, however, this should not affect the charm yield and it should be compensated by reduced branching fractions for D mesons. This is not reflected in the current data but the errors are still large. In addition, there are significant uncertainties in the D_s and Λ_c absolute branching fractions.

Table 5: Charm yield per B decay.

	Channel	Branching fraction [%] $\Upsilon(4S)$ [40]	LEP [2]
	$B \to D^0 X$	63.6 ± 3.0	57.6 ± 2.6
+	$B \to D^+ X$	23.5 ± 2.7	22.4 ± 1.9
+	$B \to D_s^+ X$	12.1 ± 1.7	19.1 ± 5.0
+	$B \to \Lambda_c^+ X$	2.9 ± 2.0	11.4 ± 2.0
+	$B \to \Xi_c^{+,0} X$	2.0 ± 1.0	6.3 ± 2.1
+	$2\times$ $B \to J/\psi_{\rm direct} X$	0.8 ± 0.08	
+	$2\times$ $B \to \psi(2S)_{\rm direct} X$	0.35 ± 0.05	
+	$2\times$ $B \to \chi_{c1} X$	0.37 ± 0.07	
+	$2\times$ $B \to \chi_{c2} X$	0.25 ± 0.1	
+	$2\times$ $B \to \eta_c X$	< 0.9 (90%C.L.)	
+	$2\times$ $b \to (c\overline{c}) X$		3.4 ± 1.2
	n_c	110 ± 5	120 ± 7

Inclusive $b \to c\overline{c}s$ transitions: It was previously assumed that the conventional $b \to c\overline{u}d \to DX$ and $b \to c\overline{c}s \to D\overline{D}_sX$ mechanisms account for all D meson production in B decay. Buchalla *et al.* [57] suggested that a significant fraction of D mesons could also arise from $b \to c\overline{c}s$ transitions with light quark pair production at the upper vertex, *i.e.* $b \to c\overline{c}s \to D\overline{D}X_s$. The two mechanisms can be distinguished by the different final states they produce. In the first case the final state includes only D mesons whereas in the second case two D mesons can be produced, one of which has to be a $\overline{D}$.

Table 6: CLEO results on $B \to DDK$ decays (preliminary).

Mode	Branching fraction [%]
$\mathcal{B}(\overline{B}^0 \to D^{*+}\overline{D}^0K^-)$	$0.45^{+0.25}_{-0.19} \pm 0.08\%$
$\mathcal{B}(B^- \to D^{*0}\overline{D}^0K^-)$	$0.54^{+0.33}_{-0.24} \pm 0.12\%$
$\mathcal{B}(\overline{B}^0 \to D^{*+}\overline{D}^{*0}K^-)$	$1.30^{+0.61}_{-0.47} \pm 0.27\%$
$\mathcal{B}(B^- \to D^{*0}\overline{D}^{*0}K^-)$	$1.45^{+0.78}_{-0.58} \pm 0.36\%$

Two routes to search for this addition to $\Gamma(b \to c\overline{c}s)$ have been pursued experimentally. In an exclusive search for $B \to D\overline{D}K$ decays CLEO required the final state to include a D and a $\overline{D}$ meson. Statistically significant signals are observed for several $D^{(*)}\overline{D}^{(*)}$ combinations. The preliminary CLEO results are listed in Table 6 [52]. While the observation of these decays proves the existence of $\overline{D}$-meson production at the upper vertex, a more inclusive measurement is needed to estimate the overall magnitude of this effect. A recent CLEO analysis exploits the fact that the flavor of the final state D-meson tags the decay mechanism. A high momentum lepton ($p_\ell > 1.4$ GeV/c) from the second B meson is used to classify the flavor of the decaying B meson. $b \to c\overline{u}d$ transitions lead to $D\ell^+$ combinations while the observation of $\overline{D}\ell^+$ identifies the new $b \to c\overline{c}s$ mechanism. Angular correlations are used to remove combinations with both particles coming from the same B meson. CLEO finds [53]

$$\frac{\Gamma(\overline{B} \to \overline{D}X)}{\Gamma(\overline{B} \to DX)} = 0.100 \pm 0.026 \pm 0.016 \ , \qquad (15)$$

which implies

$$\mathcal{B}(\overline{B} \to \overline{D}X) = 0.079 \pm 0.022 \ . \tag{16}$$

$b \to D\overline{D}X$ decays have also been observed at LEP. ALEPH [54] finds

$$\mathcal{B}(B \to D^0\overline{D}^0 X + D^0 D^{\mp} X) = 0.078^{+0.02}_{-0.018}{}^{+0.017}_{-0.015}{}^{+0.005}_{-0.004} \ , \tag{17}$$

where the last error reflects the uncertainty in D meson branching fractions. DELPHI reports the observation of $D^{*+}D^{*-}$ production [55]

$$\mathcal{B}(\overline{B} \to D^{*+}D^{*-}X) = 0.01 \pm 0.002 \pm 0.003 \ . \tag{18}$$

These results are still preliminary. We can now calculate $n_{cc} = \mathcal{B}(b \to c\overline{c}s)$. Using the data listed in Table 5 and the new result, $\mathcal{B}(\overline{B} \to \overline{D}X) = 0.079 \pm 0.022$, we find

$$n_{cc} = 23.9 \pm 3.0\% \ . \tag{19}$$

The contribution from $B \to \Xi_c^0 X$ was reduced by 1/3 to take into account the fraction that is not produced by the $b \to c\overline{c}s$ subprocess but by $b \to c\overline{u}d$ + $s\overline{s}$ quark pair production.

This result is consistent with theoretical predictions, $\mathcal{B}(b \to c\overline{c}s) = 22 \pm 6\%$ [31,56]. n_{cc} is related to n_c, the number of charm quarks produced per b decay. We expect $n_c = 1 + n_{cc} - n_{B\to \text{no charm}}$ which is consistent with the LEP result reported above. If the smaller value of n_c observed by CLEO is confirmed it could indicate a problem with $\Gamma(b \to c\overline{u}d)$ or a very large $\mathcal{B}(b \to sg)$.

Charm counting and the semileptonic branching fraction: The charm yield per B-meson decay is related to an intriguing puzzle in B physics: the experimental value for the semileptonic branching ratio of B mesons, $\mathcal{B}(B \to X\ell\nu_\ell) = 10.18 \pm 0.39\%$ $(\Upsilon(4S))$, is significantly below the theoretical lower bound $\mathcal{B} > 12.5\%$ from QCD calculations within the parton model [58]. Since the semileptonic and hadronic widths are connected via

$$1/\tau = \Gamma = \Gamma_{\text{semileptonic}} + \Gamma_{\text{hadronic}} \tag{20}$$

an enhanced hadronic rate is necessary to accommodate the low semileptonic branching fraction. The hadronic width can be expressed as

$$\Gamma_{\text{hadronic}} = \Gamma(b \to c\overline{c}s) + \Gamma(b \to c\overline{u}d) + \Gamma(b \to sg\ +\ \text{no charm})\ . \tag{21}$$

Several explanations of this $n_c/\mathcal{B}_{\text{sl}}$ discrepancy have been proposed:

1. Enhancement of $b \to c\overline{c}s$ due to large QCD corrections or a breakdown of local duality;
2. Enhancement of $b \to c\overline{u}d$ due to non-perturbative effects;
3. Enhancement of $b \to sg$ and/or $b \to dg$ due to new physics;
4. Systematic problem in the experimental results;

or the problem could be caused by some combination of the above. Arguably the most intriguing solution to this puzzle would be an enhanced $b \to sg$ rate but as we will see in the next section, new results from CLEO and LEP show no indication for new physics and place tight limits on this process.

$\mathcal{B}(b \to c\overline{u}d)$ has been calculated to next-to-leading order. Bagan *et al.* [59] find:

$$r_{ud} = \frac{\mathcal{B}(b \to c\overline{u}d)}{\mathcal{B}(b \to c\ell\nu_\ell)} = 4.0 \pm 0.4 \to \mathcal{B}(b \to c\overline{u}d)_{\text{theory}} = 41 \pm 4\%\ . \tag{22}$$

Experimentally, we can extract this quantity in the way shown in Table 7.

Table 7: Experimental extraction of $\mathcal{B}(b \to c\overline{u}d)$.

$\mathcal{B}(b \to c\overline{u}d)_{\text{exp.}} =$	$\mathcal{B}(B \to (D + \overline{D})X)$	$87.1 \pm 4.0\%$
	$+\ \mathcal{B}(B \to D_s X)_{\text{lower vertex}}$	$1.8 \pm 0.9\%$
	$+\ \mathcal{B}(B \to \text{baryons}X)$	$4.6 \pm 2.1\%$
	$-\ 2 \times \mathcal{B}(B \to \overline{D}X)_{\text{upper vertex}}$	$2 \times (7.9 \pm 2.2\%)$
	$-\ \mathcal{B}(B \to D_s X)$	$12.1 \pm 1.7\%$
	$-\ 2.25 \times \mathcal{B}(b \to c\ell\nu_\ell)$	$22.9 \pm 0.9\%$
		$43 \pm 6\%$

Here upper vertex refers to the W decay while lower vertex refers to the $b \to c$ transition. For the total semileptonic branching fraction we assumed $\mathcal{B}(b \to c\tau\nu_\tau) = 0.25 \times \mathcal{B}(b \to ce\nu_e)$. There is good agreement between theory and experiment but the errors are still too large to completely rule out an enhanced $b \to c\overline{u}d$ rate.

The theoretically preferred solution calls for an enhancement of the $b \to c\overline{c}s$ channel [31,59]. Increasing the $b \to c\overline{c}s$ component, however, would increase the average number of c quarks produced per b-quark decay as well as n_{cc}, the number of b decays with 2 charm quarks in the final state. Figure 2 taken from Ref. 1 shows the theoretical range together with experimental values from LEP and CLEO/ARGUS.

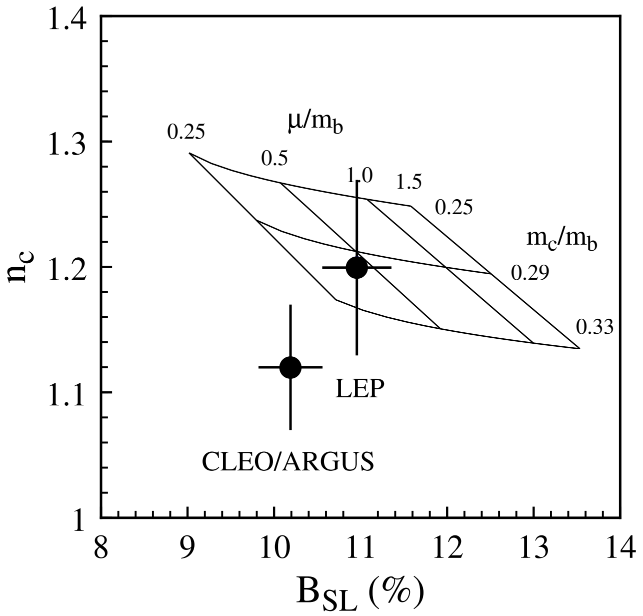

Figure 2: Charm yield (n_c) versus semileptonic branching fraction.

While the experimental value of n_{cc} is consistent with this scenario, the value of n_c measured at the $\Upsilon(4S)$ appears to be too low at the few σ-level. Systematic problems with D meson branching fractions have been pointed out as a potential solution [12] but new results from ALEPH [60] and CLEO [61] on $\mathcal{B}(D^0 \to K^-\pi^+)$ make this less likely.

After years of experimental and theoretical efforts the missing charm/$\mathcal{B}_{sl}$ problem has begun to fade away. There is still a discrepancy between the charm yield measured by CLEO and the theoretical prediction. More data are needed to either resolve this issue or to demonstrate that the problem persists.

Rare B decays: All B-meson decays that do not occur through the usual $b \to c$ transition are known as rare B decays. These include semileptonic and hadronic $b \to u$ decays that—although at tree level—are suppressed by the small CKM matrix element V_{ub} as well as higher order processes such as electromagnetic and gluonic penguin decays. Branching fractions are typically around 10^{-5} for exclusive channels and sophisticated background suppression techniques are essential for these analyses.

Arguably the most exciting new experimental results since the last edition of this review are in the field of rare B decays. For many charmless B-decay modes the addition of new data and the refinement of analysis techniques allowed CLEO to observe signals where previously there have been upper limits. For other channels new tighter upper limits have been published [62].

Semileptonic $b \to u$ transitions: The simplest diagram for a rare B decay is obtained by replacing the $b \to c$ spectator diagram a CKM suppressed $b \to u$ transition. These decays probe the small CKM matrix element V_{ub}, the magnitude of which sets bounds on the combination $\rho^2 + \eta^2$ in the Wolfenstein parameterization of the CKM matrix. Measurements of the magnitude of V_{ub} have been obtained from both inclusive and exclusive semileptonic B decays [63,65]. Inclusive analyses at the $\Upsilon(4S)$ focus on leptons in the endpoint region of the single lepton spectrum which are kinematically incompatible with coming from a $b \to c$ transition. Models are used to extrapolate to the full spectrum from which $|V_{ub}| = (3.7 \pm 0.6) \times 10^{-3}$ is extracted [64]. The error is dominated by uncertainties in the models.

Exclusive semileptonic $b \to u$ transitions have been observed by the CLEO Collaboration [63]. Using their large data sample and employing the excellent hermiticity of the CLEO II detector they were able to measure $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$ and $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) = (2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5) \times 10^{-4}$ which can be used to extract $|V_{ub}| = (3.3 \pm 0.2^{+0.3}_{-0.4} \pm 0.7) \times 10^{-3}$. The last error in these results reflects the model-dependence.

While the consistency of the two methods is encouraging, the errors, in particular the theoretical uncertainties, are still large.

Hadronic $b \to u$ transitions: Exclusive hadronic $b \to u$ transitions still await experimental discovery. Using 3.3×10^6 $B\overline{B}$ decays CLEO searched for exclusive charmless final states such as $\pi^+\pi^-$ and $\rho^+\pi^-$. No significant excess has been observed and some of the new upper limits are listed in Table 8 [66]. The mode $B^0 \to \pi^+\pi^-$ is of particular interest for CP-violation studies in the B-meson system. The branching fraction is smaller than initial expectations and extracting $\sin(2\alpha)$, *i.e.* one of the angles in the unitarity triangle, will become increasingly more difficult. Assuming factorization we can use CLEO's measurement of $B^0 \to \pi^- \ell^+ \nu_\ell$ and the ISGW II form factors [67] to predict $\mathcal{B}(B^0 \to \pi^+\pi^-) = (1.2 \pm 0.4) \times 10^{-5}$ and $\mathcal{B}(B^+ \to \pi^+\pi^0) = (0.6 \pm 0.2) \times 10^{-5}$.

Electromagnetic penguin decays: The observation of the decay $B \to K^*(892)\gamma$, reported in 1993 by the CLEO II experiment, provided first evidence for the one-loop penguin diagram [69]. Using a larger data sample the analysis was re-done in 1996 yielding [69]

$$\mathcal{B}(B \to K^*\gamma) = (4.2 \pm 0.8 \pm 0.6) \times 10^{-5} \ . \tag{23}$$

The observed branching fractions were used to constrain a large class of Standard Model extensions [72]. However, due to the uncertainties in the hadronization, only the inclusive $b \to s\gamma$ rate can be reliably compared with theoretical calculations. This rate can be measured from the endpoint of the inclusive photon spectrum in B decay. CLEO [70] found

$$\mathcal{B}(b \to s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}\,(\mathrm{CLEO}) \ . \tag{24}$$

ALEPH used a lifetime tagged sample of $Z \to b\bar{b}$ events to search for high-energy photons in the hemisphere opposite to

Table 8: Summary of new CLEO results on $B \to \pi\pi, K\pi$ and KK branching fractions. The branching fractions and the 90% C.L. upper limits are given in units of 10^{-5}. Using the notation of Gronau *et al.* [68] the last column indicates the dominant amplitudes for each decay (T, C, P, E denote tree, color suppressed, penguin, and exchange amplitudes and the unprimed (primed) amplitudes refer to $\overline{b} \to \overline{u}u\overline{d}$ ($\overline{b} \to \overline{u}u\overline{s}$) transitions, respectively.)

Mode ($B \to$)	$\mathcal{B}$	Amplitude	Theoretical expectation
$\pi^+\pi^-$	< 1.5	$-(T+P)$	0.8–2.6
$\pi^+\pi^0$	< 2.0	$-(T+C)/\sqrt{(2)}$	0.4–2.0
$\pi^0\pi^0$	< 0.93	$-(C-P)/\sqrt{(2)}$	0.006–0.1
$K^+\pi^-$	$1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.1$	$-(T'+P')$	0.7–2.4
$K^+\pi^0$	< 1.6	$-(T'+C'+P')/\sqrt{(2)}$	0.3–1.3
$K^0\pi^-$	$2.3^{+1.1}_{-1.0} \pm 0.3 \pm 0.2$	P'	0.8–1.5
$K^0\pi^0$	< 4.1	$-(C'-P')/\sqrt{(2)}$	0.3–0.8
K^+K^-	< 0.43	E	—
K^+K^0	< 2.1	P	0.07–0.13
K^0K^0	< 1.7	P	0.07–0.12
$(K^+$ or $\pi^+)\pi^0$	$1.6^{+0.6}_{-0.5} \pm 0.3 \pm 0.2$	—	—

the tag. This allows them to measure the photon spectrum from B decays which ultimately leads to [71]

$$\mathcal{B}(b \to s\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}\,(\mathrm{ALEPH})\ . \qquad (25)$$

Our theoretical understanding of inclusive $b \to s\gamma$ transitions has been significantly enhanced by two new calculations that now include all terms to next-to-leading order [73]. The expected Standard Model rate, while slightly larger now, is still consistent with both the CLEO and ALEPH results. The substantially reduced uncertainties result in tighter constraints on new physics such as double Higgs models [2].

Gluonic penguin decays: A larger total rate is expected for gluonic penguins, the counterpart of $b \to s\gamma$ with the photon replaced by a gluon.

Experimentally, it is a major challenge to measure the inclusive $b \to sg$ rate. The virtual gluon hadronizes as a $q\overline{q}$ pair without leaving a characteristic signature in the detector.

CLEO extended $D - \ell$ correlation measurements described in the section on hadronic B decays to obtain the flavor specific decay rate $\Gamma(\overline{B} \to DX)_{\rm lower\ vertex}/\Gamma_{\rm total}$. This quantity should be 1 minus corrections for charmonium production, $b \to u$ transitions, $B \to$ baryons, and D_s production at the lower vertex. Most importantly, the $b \to sg$ rate must also be subtracted. To remove uncertainties due to $\mathcal{B}(D^0 \to K^-\pi^+)$ CLEO normalizes to $\Gamma(\overline{B} \to DX\ell\nu_\ell)/\Gamma(\overline{B} \to X\ell\nu_\ell)$. Their preliminary result is

$$\frac{\Gamma(\overline{B} \to DX)_{\rm lower\ vertex}/\Gamma_{\rm total}}{\Gamma(\overline{B} \to DX\ell\nu_\ell)/\Gamma(\overline{B} \to X\ell\nu_\ell)} = 0.901 \pm 0.034 \pm 0.014 \quad (26)$$

whereas $0.903 \pm 0.018 - \mathcal{B}(b \to sg)$ was expected. This corresponds to an upper limit of $\mathcal{B}(b \to sg) < 6.8\%$ [53]. DELPHI [55] studied the the p_T spectrum of charged kaons in B decays and found a model-dependent limit $\mathcal{B}(b \to sg) < 5\%$ (95% C.L.). These results agree well with the Standard Model prediction of $\mathcal{B}(\overline{B} \to \text{no charm}) = (1.6 \pm 0.8)\%$ [74] and there is little experimental support for new physics and an enhanced $b \to sg$ rate [75]. However, experimental uncertainties are still large and it is too early to draw final conclusions. Last summer, the SLD collaboration reported an excess in the kaon spectrum at high p_T [76].

Exclusive decays such as $B^0 \to K^+\pi^-$ are strongly suppressed to first order and are expected to proceed via loop processes. CLEO studied these decay modes and last summer reported the first observation of $B^0 \to K^+\pi^-$ and $B^+ \to K^0\pi^+$ decays. The results are listed in Table 8. $\mathcal{B}(B^+ \to K^0\pi^+)$ is of particular interest since it directly measures the strength of the gluonic penguin amplitude (Table 8). The smaller rate measured for $B^0 \to K^+\pi^-$ could indicate that the two amplitudes contributing to this channel interfere destructively. This observation has been extended by Fleischer and Mannel [77] to place some constraints on γ, the phase of V_{ub}.

CLEO extended their search of charmless B decay to modes including light meson resonances such as ρ, K^*, ω, η, and η' [78]. Statistically significant signals have been seen in several channels; the results are summarized in Table 9.

Table 9: Summary of new CLEO results on rare B decays involving light meson resonances.

Mode	Branching fraction ($\times 10^{-5}$)
$B \to \omega K^+$	$1.5^{+0.7}_{-0.6} \pm 0.3$
$B \to \eta' K^+$	$7.1^{+2.5}_{-2.1} \pm 0.9$
$B \to \eta' K^0$	$5.3^{+2.8}_{-2.2} \pm 1.2$
$B \to \eta' X_s$	$62 \pm 16 \pm 13$
	$(2.0 < p_{\eta'} < 2.7\,\mathrm{GeV/c})$

A surprisingly large signal has been observed for $B \to \eta' K$ (see Fig. 3) while no evidence for ηK or $\eta' K^*$ final states has been found [79].

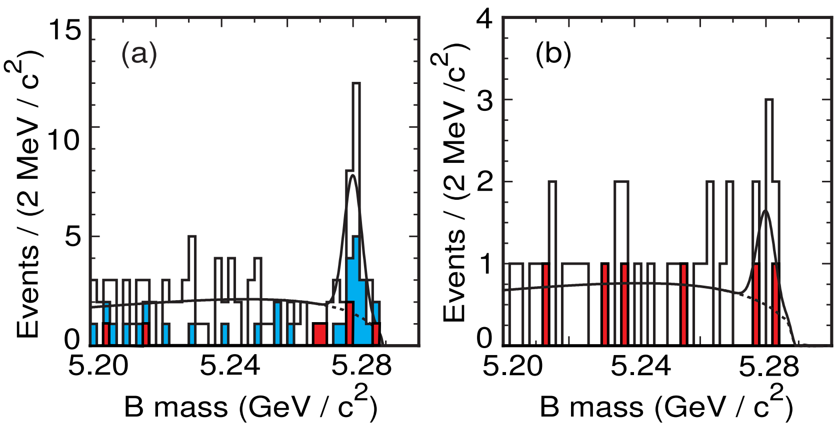

Figure 3: Beam-constrained mass for (a) $B^+ \to \eta' h^+$ with $h^+ = K^+$ or π^+ and (b) $B^0 \to \eta' K^0$. A likelihood analysis shows that the $B^+ \to \eta' h^+$ channel is dominated by $\eta' K^+$. (CLEO)

The interpretation of these results is subject of an ongoing discussion. It has been suggested that interference between different penguin amplitudes causes $\mathcal{B}(B \to \eta' K)$ to be larger than $\mathcal{B}(B \to \eta K)$ [80,81]. Other proposals try to explain the large $\eta' K$ rate by the anomalous coupling of the η' to glue [82,83], a $c\bar{c}$ component in the η' [84] or by an enhanced $b \to sg$ rate due to some new physics [85]. Additional experimental input to this puzzle comes from a CLEO measurement of inclusive η' production. At high momenta the η' spectrum is dominated by $B \to \eta' X_s$ decays and a study of the system recoiling against the η' shows that large masses $m(X_s)$ are preferred [86].

In summary, gluonic penguin decays have been established. Many decay modes have been observed for the first time and the emerging pattern is full of surprises. The observed penguin effects are large and while old favorites such as $B^0 \to \pi^+\pi^-$ might be less useful for CP-violation studies there is hope that new opportunities will open up.

Outlook: With the next Fermilab collider run still years away and LEP running at higher energies it is not likely that the B-meson lifetimes presented in this edition will change substantially over the next two years. Nor should we expect many new results on b-hadron spectroscopy. In the short term, CLEO is still taking data and so is SLD. The SLD collaboration expects to collect half a million hadronic Z events. Combining this with the excellent resolution of the SLD vertex detector could push the sensitivity on B_s mixing up to $\Delta m_s = 15$ ps^{-1}. We have just began to observe rare B decays and already now we see many intriguing patterns: Why is $B \to \eta' K$ so large? Where are the $B^0 \to \pi^+\pi^-$ events? The size of the CLEO data sample will soon reach the 10 fb^{-1} mark and many results, answers and new questions should be expected.

In the long term, which is actually only a year away, the next generation of B experiments will come on line: BaBar, BELLE, CLEO III, as well as HERA-B. So there is hope that in two years when the next edition of this *Review* will be written we have reached another milestone in our understanding of B mesons and b baryons.

References

1. M. Neubert, CERN-TH/98-2, `hep-ph/9801269`, *Proceedings of the 1997 EPS Conference*, Jerusalem (1997).
2. P. Drell, CLNS-97-1521, `hep-ex/9711020`, *Proceedings of the 18th International Symposium on Lepton-Photon Interactions*, Hamburg (1997).

3. O. Schneider, CERN-PPE/97-143, *Proceedings of the 18th International Symposium on Lepton-Photon Interactions*, Hamburg (1997).
4. T.E. Browder, K. Honscheid, and D. Pedrini, Ann. Rev. Nucl. Sci. **46**, 395 (1996).
5. CLEO Collab., B. Barish *et al.*, Phys. Rev. Lett. **76**, 1570 (1996).
6. CLEO Collab., B. Barish *et al.*, Phys. Rev. **D51**, 1014 (1995).
7. CLEO Collab., C.P. Jessop *et al.*, Phys. Rev. Lett. **79**, 4533 (1997).
8. The LEP B oscillations working group, "Combined results on B^0 oscillations: Results for Particle Data Group 1998," LEPBOSC 98/2;
See also `http://www.cern.ch/LEPBOSC/combined_results/PDG_1998/`;
For latest information see:
`http://www.cern.ch/LEPBOSC/`.
9. J. Hagelin, Nucl. Phys. **B193**, 123 (1981). See also A.J. Buras, W. Stominiski, and H. Steger, Nucl. Phys. **B245**, 369 (1984);
M.B. Voloshin, N.G. Uraltsev, V.A. Khoze, and M.A. Shifman, Sov. J. Nucl. Phys. **46**, 112 (1987).
10. R. Aleksan, A. Le Yaouanc, L. Oliver, O. Pène, and J.C. Raynal, Phys. Lett. **B316**, 567 (1993).
11. T.E. Browder and S. Pakvasa, Phys. Rev. **D52**, 3123 (1995).
12. I. Dunietz, FERMILAB-PUB 96/104-T, `hep-ph/9606247`.
13. CDF Collab., Discovery of the B_c meson, `http://www-cdf.fnal.gov/physics/new/bottom/bc/bc_exec/bc_exec.html`.
14. M. Feindt, contribution to the *Proceedings of the Hadron 95 Conference*, Manchester, UK (1995).
15. DELPHI Collab., EPS0565, contribution to the 1995 Europhysics Conference, Brussels, Belgium (1995), and the Beijing Lepton-Photon Symposium (1995).
16. M. Feindt, contribution to the *Proceedings of the 2nd International Conference on B Physics and CP Violation*, Honululu (1997).
17. I.I. Bigi, B. Blok, M. Shifman, N. Uraltsev, and A. Vainshtein, contribution to "B Decays," ed. S. Stone, World Scientific (1994), and also available as CERN-THS-7132/94 (1994).

18. M. Beneke, G. Buchalla, and I. Dunietz, Phys. Rev. **D54**, 4419 (1996).
19. J. Alcaraz, L. Di Ciaccio, T. Hessing, D. Koetke, I.J. Kroll, H.G. Moser, and C. Shepherd-Themistocleous (LEP B Lifetime Group).
20. L. Di Ciaccio *et al.*, Oxford University preprint OUNP 96-05 (1996), Rome University preprint ROM2F/96/09 (1996), Max Planck Institute Munich MPI-PhE/96-05 (1996).
21. D. Buskulic *et al.*, ALEPH Collab., Phys. Lett. **B369**, 151 (1996).
22. M. Acciarri *et al.*, L3 Collab., Phys. Lett. **B416**, 220 (1997).
23. P.D.Acton *et al.*, OPAL Collab., Z. Phys. **C60**, 217 (1993).
24. D. Buskulic *et al.*, ALEPH Collab., Phys. Lett. **B314**, 459 (1993).
25. P. Abreu *et al.*, DELPHI Collab., Z. Phys. **C63**, 3 (1994).
26. P. Abreu *et al.*, DELPHI Collab., Phys. Lett. **B377**, 195 (1996).
27. M. Acciarri *et al.*, L3 Collab., Phys. Lett. **B416**, 220 (1997).
28. K. Ackerstaff *et al.*, OPAL Collab., Z. Phys. **C73**, 397 (1997).
29. K. Abe *et al.*, SLD Collab., Phys. Rev. Lett. **75**, 3624 (1995).
30. F. Abe *et al.*, CDF Collab., Fermilab-Pub-97/352-E, submitted to Phys. Rev. D.
31. M. Neubert, C. T. Sachrajda, Nucl. Phys. **B483**, 339 (1997).
32. J.L. Rosner, Phys. Lett. **B379**, 267 (1996).
33. P. Colangelo and F. De Fazio, Phys. Lett. **B387**, 371 (1996) and P. Colangelo, *Proceedings of the 28th International Conference on High Energy Physics*, Warsaw (1996).
34. See the "Note on B^0–$\overline{B}^0$ Mixing" by H. Quinn in this *Review*.
35. N. Isgur and M. B. Wise, Phys. Lett. **B232**, 113 (1989);
    N. Isgur and M. B. Wise, Phys. Lett. **B237**, 527 (1990).
36. CLEO Collab., M. Athanas *et al.*, Phys. Rev. Lett. **79**, 2208 (1997).
37. ALEPH Collab., D. Buskulic *et al.*, Phys. Lett. **B395**, 373 (1997).

38. CLEO Collab., J.E. Duboscq *et al.*, Phys. Rev. Lett. **76**, 3898 (1996);
CLEO Collab., CLEO-CONF 96-8.

39. J.D. Richman and P.R. Burchat, Rev. Mod. Phys. **67**, 893 (1995).

40. K. Honscheid, contribution to the *Proceedings of the International b20 Symposium*, Chicago (1997).

41. CLEO Collab., B. Nemati *et al.*, CLNS 97/1503, `hep-ex/9708033`, to appear in Phys. Rev. D.

42. M. Neubert and B. Stech, CERN-TH/97-99, `hep-ph/9705292`, to appear in "Heavy Flavours," 2nd edition, eds. A.J. Buras and M. Lindner.

43. M. Neubert, V. Rieckert, Q. P. Xu and B. Stech in *Heavy Flavours*, edited by A. J. Buras and H. Lindner (World Scientific, Singapore, 1992).

44. B. Blok and M. Shifman, Nucl. Phys. **B389**, 534 (1993).

45. A. Buras, Max Planck Institute preprint MPI-PhT/94-60, TUM-T31-75/94.

46. B. Stech, contribution to the *Proceedings of the International b20 Symposium*, Chicago (1997).

47. B. Tseng, H.N. Li, `hep-ph/9712527`.

48. CLEO Collab., G. Brandenburg *et al.*, CLNS 97/1485, to appear in Phys. Rev. Lett.

49. CLEO Collab., J. Gronberg *et al.*, CLEO-CONF 96-25.

50. M. Gronau and D. Wyler, Phys. Lett. **B265**, 172 (1991).

51. CLEO Collab., M. Athanas *et al.*, CLNS 98/1541., submitted to Phys. Rev. Lett.

52. CLEO Collab., CLEO-CONF-97-26.

53. CLEO Collab., T.E. Coan *et al.*, Phys. Rev. Lett. **80**, 1150 (1998).

54. ALEPH Collab., R. Barate *et al.*, CERN-EP/98-037, submitted to Eur. Phys. J. C.

55. DELPHI Collab., ICHEP96 PA01-108, DELPHI 96-97 CONF 26.

56. W.F. Palmer and B. Stech, Phys. Rev. **D48**, 4174 (1993).

57. G. Buchalla, I. Dunietz, H. Yamamoto, Phys. Lett. **B364**, 188 (1995).

58. I. Bigi, B. Blok, M.A. Shifman and A. I. Vainshtein, Phys. Lett. **B323**, 408 (1994).

59. E. Bagan, P. Ball, V.M. Braun, and P. Gosdzinsky, Phys. Lett. **B342**, 362 (1995); Erratum Phys. Lett. **B374**, 363 (1996).

60. ALEPH Collab., R. Barate *et al.*, Phys. Lett. **B405**, 191 (1997).
61. CLEO Collab., M. Artuso *et al.*, CLNS 97/1517, to appear in Phys. Rev. Lett.
62. P. Abreu *et al.*, CERN-EP/08-07, accepted by Phys. Lett.
63. CLEO Collab., J.P. Alexander *et al.*, Phys. Rev. Lett. **77**, 5000 (1996).
64. L.K. Gibbons, contribution to the *Proceedings of the 7th International Symposium on Heavy Flavor Physics*, Santa Barbara (1997).
65. CLEO Collab., J. Bartelt *et al.*, Phys. Rev. Lett. **71**, 511 (1993);
S. Stone, "Semileptonic B Decays, B decays," ed. S. Stone, World Scientific (1994).
66. CLEO Collab., R. Godang *et al.*, CLNS 97/1522, to appear in Phys. Rev. Lett.
67. N. Isgur and D. Scora, Phys. Rev. **D52**, 2783 (1995).
68. M. Gronau, O.F. Hernandez, D. London, J.L. Rosner, Phys. Rev. **D52**, 6356 (1995).
69. CLEO Collab., R. Ammar *et al.*, Phys. Rev. Lett. **71**, 674 (1993), CLEO CONF 96-05.
70. CLEO Collab., M.S. Alam *et al.*, Phys. Rev. Lett. **74**, 2885 (1995).
71. ALEPH Collab., R. Barate *et al.*, CERN-EP/98-044, to appear in Phys. Lett. B.
72. J.L. Hewett, Phys. Rev. Lett. **70**, 1045 (1993).
73. K.G. Chetyrkin, M. Misiak and M. Munz, Phys. Lett. **B400**, 206 (1997);
A.J. Buras, A. Kwiatkowski and N. Pott, TUM-HEP-287/97.
74. A. Lenz, U. Nierste, G. Ostermaier, Phys. Rev. **D56**, 7228 (1997).
75. A.L. Kagan and J. Rathsman, `hep-ph/9701300`, and A.L. Kagan, *Proceedings of the 1997 EPS Conference*, Jerusalem (1997).
76. M. Douadi, *Proceedings of the 1997 EPS Conference*, Jerusalem (1997).
77. R. Fleischer and T. Mannel, LP-021/022, contributed to the XVIII International Symposium on Lepton-Photon Interactions, Hamburg (1997).
78. A.J. Weinstein, contribution to the *Proceedings of Beauty 97*, Los Angeles (1997).

79. CLEO Collab., B. Behrens *et al.*, CLNS 97/1536, submitted to Phys. Rev. Lett..
80. H.J. Lipkin, Phys. Lett. **B254**, 247 (1991).
81. A.S. Dighe, M. Gronau and J.L. Rosner, Phys. Rev. Lett. **79**, 4333 (1997).
82. D. Atwood and A. Soni, Phys. Lett. **B405**, 150 (1997).
83. M. Gronau and J.L. Rosner, Phys. Rev. **D53**, 2516 (1996);
W.S. Hou and B. Tseng Phys. Rev. Lett. **80**, 434 (1998);
X.G. He, W.S. Hou and C.S. Huang, `hep-ph/9712478`;
H. Fritzsch, Phys. Lett. **B414**, 83 (1997).
84. I. Halperin and A.R. Zhitnitsky, Phys. Rev. **D56**, 7247 (1997);
E.V. Shuryak and A.R. Zhitnitsky, NI-97033-NQF, `hep-ph/9706316`;
F. Yuan and K.T. Chao, Phys. Rev. **D56**, 2495 (1997).
85. A.L. Kagan and A.A. Petrov, UCHEP-27, `hep-ph/9707354`.
86. CLEO Collab., CLEO-CONF 97-13.