PRODUCTION AND DECAY OF *b*-FLAVORED HADRONS

Updated March 2002 by L. Gibbons (Cornell University, Ithaca) and K. Honscheid (Ohio State University, Columbus).

In the summer of 2001—almost four decades after CP violation was first discovered in the decay of neutral kaons—the BABAR and Belle collaborations reported the first observation of CP violation in the B meson system [1,2]. The measurement of the CP-violation parameter $\sin(2\beta)$ marks the culmination of a very significant experimental and theoretical program that started in 1973 when Kobayashi and Maskawa proposed their model of the quark mixing matrix. Other recent developments in the physics of B mesons include new results on penguin decays, improved measurements of rare hadronic B decays, as well as new determinations of the CKM matrix elements V_{cb} and V_{ub}.

Since the last edition of this review, the experimental landscape in B physics has changed dramatically. The BABAR and Belle experiments have been extremely successful. The analyses of the data collected by the LEP experiments and during the first run of the Tevatron collider have been completed, and after 20 years of B physics, the CLEO collaboration has decided to leave the Υ resonance region and to focus on charm and QCD studies at lower energies. The structure of this review has also changed. After a brief description of the experimental observation of CP violation, we briefly update the results on b quark production and lifetimes. Since this edition features separate reviews on the determination of the CKM matrix elements V_{cb} and V_{ub}, we have removed the section on semileptonic B decays [3–4]. This review closes with a short update on hadronic and rare decays of B mesons.

CP Violation in the B Meson System: The regular pattern of the three lepton and quark families is one of the most intriguing puzzles in particle physics. The existence of families gives rise to many of the free parameters in the Standard Model, in particular the fermion masses, and the elements of the Cabibbo-Kobayashi-Maskawa matrix (CKM) that describe the mixing between quark generations. In the Standard Model of three generations, the CKM matrix is defined by three real parameters and one complex phase. A more detailed discussion of the CKM matrix and CP violation can be found elsewhere in this Review [5–6].

The determination of all of these parameters is required to fully define the Standard Model, and is central to the experimental and theoretical program in heavy-flavor physics. In the framework of the Standard Model, the CKM matrix must be unitary, *i.e.*, $VV^\dagger = 1$. This gives rise to relationships between the matrix elements that can be visualized as triangles in the complex plane, for example

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0\,. \tag{1}$$

Measurements of the magnitudes of the CKM elements, such as $|V_{ub}|$ and $|V_{cb}|$, determine the lengths of the sides of the triangle. The interior angles of the triangle which can also be expressed in terms of the CKM elements

$$\alpha = \phi_2 = arg(-\frac{V_{ud}V^*_{ub}}{V_{td}V^*_{tb}})\,, \tag{2}$$

$$\beta = \phi_1 = arg(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}})\,, \text{ and} \tag{3}$$

$$\gamma = \phi_3 = arg(-\frac{V_{cd}V^*_{cb}}{V_{ud}V^*_{ub}}) \tag{4}$$

are accessible by measurements of CP asymmetries. Initial results on the angle β have been reported previously by the CDF, OPAL and ALEPH collaborations, but last summer Belle and BABAR announced new results with errors small enough to claim the observation of CP violation in the decay of neutral B mesons. Both experiments[1] determine $\sin(2\beta)$ by measuring the time dependent CP asymmetry defined as

$$A_f = \frac{\Gamma(B^0 \to f_{CP}) - \Gamma(\overline{B}^0 \to f_{CP})}{\Gamma(B^0 \to f_{CP}) + \Gamma(\overline{B}^0 \to f_{CP})} = -\xi_f \sin(2\beta)\sin(\Delta m(t_2 - t_1)) \tag{5}$$

[1] The authors would like to thank Tom Browder for providing detailed information on the measurement of $\sin(2\beta)$.

where Δm is the mass difference between the two B^0-mass eigenstates, ξ_f denotes the the CP value of the final state (± 1), and t_1 and t_2 are the proper times for the tagged B and the other B decaying to the CP eigenstate, respectively [7]. The equation for A_f given above is correct at the $\Upsilon(4S)$ resonance, where the B meson pair is produced in an odd orbital angular momentum state ($L = 1$). In this case, the time-integrated asymmetry is identically zero, and hence, time-dependent measurements are necessary. Given the short B meson lifetime and the small energy release in $\Upsilon \rightarrow B\overline{B}$, this requires asymmetric beam energies to boost the $\Upsilon(4S)$ center of mass frame. At KEK-B, for example, the boost is $\beta\gamma = 0.43$, and the typical B meson decay length is dilated from ≈ 20 μm to ≈ 200 μm. PEP-II uses a slightly larger boost, $\beta\gamma = 0.55$.

The measurement of A_f or $\sin(2\beta)$ requires the reconstruction of the CP final state (f_{CP}), the tagging of the b-quark flavor, and the determination of Δt—the proper time difference between the two B-meson decays. Unbinned likelihood fits are used to extract the CP-violating phase from the measured $A_f(\Delta t)$ distributions. Both experiments use $B \rightarrow$ charmonium decays such as $J/\psi K_S$, $J/\psi K_L$, $\psi(2S)K_S$, $\chi_{c1}K_S$, and $J/\psi K^{*0}, K^{*0} \rightarrow K_S\pi^0$. In a sample consisting of 32 million $B\overline{B}$ pairs, BABAR extracted a total of 1230 events over a background of 200 events. Belle's CP-eigenstate event sample consists of 1316 events, with a background of 281.6 events. The b-quark flavor of the accompanying B meson is identified using the charge of leptons, kaons, slow pions from $D^{*+} \rightarrow D^0\pi^+$, or fast pions from two-body B decays, such as $\overline{B}^0 \rightarrow D^{*+}\pi^-$. Summed over all tagging categories, both experiments achieve similar effective tagging efficiencies. Belle finds $\epsilon_{\rm eff} = 0.270 \pm 0.008^{+0.006}_{-0.009}$ and BABAR reports $\epsilon_{\rm eff} = 0.261 \pm 0.012$. Here $\epsilon_{\rm eff}$ is defined as $\epsilon_{\rm eff} = \epsilon(1 - 2\omega)^2$. ω is the mis-tagging probability. For the final ingredient to the CP-asymmetry measurement, the lifetime difference Δt, the two B-meson decay vertices are reconstructed using the information provided by the experiment's high resolution silicon vertex detectors. The vertex finding efficiency is typically around 95%. So far, only the vertex separation, Δz, along the beam axis has been used. RMS resolutions are typically $\sigma_{\Delta z} \approx 180\mu m$. Once the B-decay vertices are reconstructed, the proper time difference is calculated from $\Delta z/\gamma\beta$. In the summer of 2001, these analyses led to the first significant measurements of $\sin(2\beta)$. BABAR found [1]

$$\sin(2\beta) = \sin(2\phi_1) = 0.59 \pm 0.14 \pm 0.05\,, \tag{6}$$

and Belle reported [2]

$$\sin(2\beta) = \sin(2\phi_1) = 0.99 \pm 0.14 \pm 0.06\,. \tag{7}$$

Both experiments have updated their results at the 2002 winter conferences. Using almost twice the data sample (62 million $B\overline{B}$ pairs), BABAR [8] obtained $\sin(2\beta) = 0.75 \pm 0.09 \pm 0.04$, while with 42 million $B\overline{B}$ pairs, Belle [9] reported $\sin(2\beta) = 0.82 \pm 0.12 \pm 0.05$. Averaging the latest results from the two experiments we find

$$\sin(2\beta) = \sin(2\phi_1) = 0.78 \pm 0.08\,. \tag{8}$$

This establishes violation of CP invariance in the decay of neutral B mesons. The value found for $\sin(2\beta)$ is consistent with Standard Model expectations.

Experimental work on the determination of the other two angles of the unitarity triangle has just begun. Much larger data samples will be needed to obtain precision results and to challenge the Standard Model. Information on $\sin(2\alpha)$ can be extracted from $B \to \pi^+\pi^-$ decays following a procedure similar to the one outlined above. Unfortunately, these decays suffer from fairly small branching fractions ($\mathcal{O}(10^{-6})$), and they receive sizeable contributions from penguin diagrams that complicate the extraction of the CP phases. Because of this, the time-dependent asymmetry in $B \to \pi^+\pi^-$ will not be proportional to $\sin(2\alpha)$, but to $\sin(2\alpha_{\rm eff})$, with an unknown and possibly large correction. Despite these difficulties, first attempts to measure CP asymmetries in the $\pi^+\pi^-$ mode have been reported. Using 30 fb^{-1}, BABAR [10] extracts $S = \sin(2\alpha_{\rm eff}) = -0.01 \pm 0.37 \pm 0.11$ and Belle [9] finds $S = -1.21^{+0.38}_{-0.27}\,^{+0.16}_{-0.13}$. Identification of S, the amplitude of the $\sin(\Delta m \Delta t)$ term in the time–dependent asymmetry, with

$\sin(2\alpha_{\text{eff}})$ assumes that there is contribution from direct CP violation in the decay. A sign of direct CP violation would be an additional cosine component with a nonzero amplitude C, and in this case $\sin(2\alpha_{\text{eff}})$ must be extracted using both S and C. Both BABAR and Belle have measured C simultaneously with S. BABAR finds $C = -0.02 \pm 0.29 \pm 0.07$, consistent with no direct CP violation, while Belle reports an indication of direct CP violation in $B^0 \to \pi^+\pi^-$ with $C = +0.94^{+0.25}_{-0.31} \pm 0.09$.

Several methods have been suggested to measure the third angle, γ (see, for example reference [11]). However, they require very large data samples (such as for $B \to DK$), measurements of B_s decays or suffer from large theoretical uncertainties, rendering γ particularly difficult to measure.

Production and spectroscopy: Elementary particles are characterized by their masses, lifetimes, and internal quantum numbers. The bound states with a $\overline{b}$ quark and a u or 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. By far the largest samples of B mesons have been collected by the B-factory experiments. Both Belle and BABAR have accumulated approximately 70 fb^{-1} and expect to reach 100 fb^{-1} this summer. Most new results from CLEO are based on a sample of $\approx 9.7 \times 10^6$ $B\overline{B}$ events. At the Tevatron, CDF in particular has made significant contributions with 100 pb^{-1} of data. Operating at the Z resonance, each of the four LEP collaborations recorded slightly under a million $b\overline{b}$ events, while the SLD experiment collected about 0.1 million $b\overline{b}$ events.

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 [12]. CLEO [13] and BABAR [14] have measured the ratio of charged to neutral $\Upsilon(4S)$ decays using exclusive $B \to \psi K^{(*)}$ decays. Assuming isospin invariance and $\tau_{B^+}/\tau_{B^0} = 1.066 \pm 0.024$, we average their results to

$$\frac{f_+}{f_0} = \frac{\mathrm{B}(\Upsilon(4S) \to B^+B^-)}{\mathrm{B}(\Upsilon(4S) \to B^0\overline{B}^0)} = 1.072 \pm 0.045 \pm 0.027 \pm 0.024 \ , \tag{9}$$

where the uncertainties are the combined experimental statistical, combined experimental systematic, and the lifetime ratio uncertainty, respectively. 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. Again using exclusive $B \to J/\psi K^{(*)}$ decays, CLEO determined these masses to $m(B^0) = 5.2791 \pm 0.0007 \pm 0.0003$ GeV/c^2 and $m(B^+) = 5.2791 \pm 0.0004 \pm 0.0004$ GeV/c^2, respectively [15].

At high-energy collider experiments, b quarks hadronize as $\overline{B}^0$, B^-, $\overline{B}^0_s$, and B_c^- mesons, or as baryons containing b quarks.

Over the last few years, there have been significant improvements in our understanding of the b-hadron sample composition. Table 1 summarizes the results showing the fractions f_d, f_u, f_s, and f_{baryon} of B^0, B^+, B^0_s, and b baryons in an unbiased sample of weakly decaying b hadrons produced at the Z resonance and in $p\overline{p}$ collisions. A detailed account can be found elsewhere in this Review [16]. The values assume identical hadronization in $p\overline{p}$ collisions and in Z decay, even though these could, in principle, differ because of the different transverse momentum distributions of the b–quark in these processes.

To date, the existence of several b-flavored mesons (B^-, $\overline{B}^0$, B_s, B_c, and various excitations), as well as the Λ_b baryon has been established. The current world average of the B^*–B mass difference is 45.78 ± 0.35 MeV/c^2. 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 the precision of a few MeV. The current world averages of the B_s and the Λ_b mass are 5.3696 ± 0.0024 GeV/c^2 and 5.624 ± 0.009 GeV/c^2, respectively.

Table 1: Fractions of weakly decaying b-hadron species in $Z \to b\overline{b}$ decay and in $p\overline{p}$ collisions at $\sqrt(s) = 1.8$ TeV.

b hadron	Fraction [%]
B^-, $\overline{B}^0$	38.8 ± 1.3
$\overline{B}^0_s$	10.6 ± 1.3
b baryons	11.8 ± 2.0

Clear evidence for the B_c, the last weakly decaying bottom meson, has been published by CDF [17]. They reconstruct the semileptonic decay $B_c \to J/\psi \ell X$, and extract a B_c mass of $6.40 \pm 0.39 \pm\ 0.13$ GeV/c^2.

First indications of Ξ_b production have been presented by the LEP Collaborations [18–19].

Excited B-meson states have been observed by CLEO, LEP, CUSB, and CDF. Evidence for B^{**} production has been presented by the LEP and CDF experiments [20]. Inclusively reconstructing a bottom hadron candidate combined with a charged pion from the primary vertex, they see the B^{**} as a broad resonance around 5.697 ± 0.009 GeV/c^2 in the $M(B\pi) - M(B)$ mass distribution [21]. Due to the inclusive approach, the mass resolution is limited to about 40 MeV, which makes it very difficult to identify the narrow states, B_1 and B_2^*, separately. The LEP experiments have also provided evidence for excited B_s^{**} states.

Lifetimes: Precise lifetimes are key in extracting the weak parameters that are important for understanding the role of the CKM matrix in CP violation, such as the determination of V_{cb} and $B_s\overline{B}_s$ mixing measurements. 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

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

Particle	Lifetime [ps]
B^0	1.542 ± 0.016
B^+	1.674 ± 0.018
B_s	1.461 ± 0.057
B_c	$0.46^{+0.18}_{-0.16} \pm 0.03$
b baryon	1.208 ± 0.051
Λ_b	1.229 ± 0.080
Ξ_b	$1.39^{+0.34}_{-0.28}$
b hadron	1.564 ± 0.014

should be significantly smaller, of order 10% or less [22]. For the b system we expect

$$\tau(B^-) \ \geq \ \tau(\overline{B}^0) \ \approx \ \tau(B_s) \ > \ \tau(\Lambda_b^0) \ \gg \ \tau(B_c) \ . \qquad (10)$$

In the B_c, both quarks can decay weakly, resulting in its much shorter lifetime. 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.

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 [23]. 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 [24]. The B factories are now contributing to the lifetime measurements. Their use of fully–reconstructed B decays will contribute measurements with complementary systematic. The measurements are free, for example, from systematics associated with modeling of fragmentation. The new world average b-hadron lifetimes are summarized in Table 2.

For comparison with theory, lifetime ratios are preferred. Experimentally we find [23]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.083 \pm 0.017\,, \ \frac{\tau_{B_s}}{\tau_{B^0}} = 0.947 \pm 0.038\,,$$

$$\frac{\tau_{\mathrm{b-Hadron}}}{\tau_{B^0}} = 0.783 \pm 0.034\,, \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.797 \pm 0.053\,, \qquad (11)$$

while theory makes the following predictions [25]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1 + 0.05 \left(\frac{f_B}{200 \ \mathrm{MeV}}\right)^2 \ , \ \frac{\tau_{B_s}}{\tau_{B^0}} = 1 \pm 0.01 \ , \ \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.9 \ . \qquad (12)$$

In conclusion, the pattern of measured B-meson lifetimes follows the theoretical expectations, and non-spectator effects are observed to be small. The short B_c lifetime has been predicted correctly. 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 [26–32].

Similar to the kaon system, neutral B mesons contain short- and long-lived components. The lifetime difference is, of course, significantly smaller, and recent experimental limits at 95% C.L. are

$$\frac{\Delta\Gamma_d}{\Gamma_d} \ < \ 0.8 \ \text{ and } \ \frac{\Delta\Gamma_s}{\Gamma_s} \ < \ 0.52 \ . \qquad (13)$$

These results are based on a comparison of direct Δm measurements with χ_d measurements for B_d [33] and a combination [34,35] of the various B_s proper time measurements. A more restrictive limit for the B_s system can be obtained if one assumes $\Gamma_{B_s} = \Gamma_{B_d}$.

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 excellent laboratory to study perturbative and non-perturbative QCD, hadronization, and Final State Interaction (FSI) effects.

The precision of the experimental data has steadily improved over the past years. Belle, BABAR and CLEO updated most branching fractions for exclusive $B \to J/\psi K^{(*)}$ transitions. Several new $B \to$ charmonium modes have been added. Updated measurements of the polarization in $B \to J/\psi K^*$ resolved an outstanding discrepancy between theory and experiment [36]. Angular distributions have been studied for other B decays with two vector mesons in the final state, including $B \to D^*\rho$, $B \to D^*D^*$, and $B \to D^*D_s^*$. CLEO found the relative phases of the helicity amplitudes in $B \to D^*\rho^-$ decays to be non-zero [37], implying that FSI effects may play a role in B decays after all. $B^0 \to D^{*+}D^{*-}$ decays have been observed with a branching fraction of $(8.3 \pm 1.6 \pm 1.2) \times 10^{-4}$, providing unambiguous evidence for Cabibbo–suppressed $b \to ccd$ transitions [38]. BABAR studied the polarization of these final states and found a CP odd component of $0.22 \pm 0.18 \pm 0.03$ [38].

Gronau and Wyler [39] first suggested that decays of the type $B \to DK$ can be used to extract the angle γ of the CKM unitarity triangle, $\gamma \approx \arg(V_{ub})$. Examples of such Cabibbo–suppressed modes have been observed by CLEO, Belle and BABAR. The current world average branching fraction for $\mathrm{B}(B^- \to D^0K^-)$ is $(3.8 \pm 0.6) \times 10^{-4}$.

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. Recent theoretical work has provided a more solid foundation for this hypothesis [40].

By comparing exclusive hadronic B decays to the corresponding semileptonic modes, the factorization hypothesis has been experimentally confirmed for certain $b \to c$ decays with large energy release [36]. An example is given by the longitudinal polarization of ρ mesons in $B \to D^*\rho$ decays [37]. CLEO's result of $\Gamma_L/\Gamma = 0.878 \pm 0.034 \pm 0.040$ agrees well with the factorization expectation, 0.85–0.88 [41–44]. Within the experimental precision (10 - 30%) and over the limited q^2 range probed so far, the measurements agree with factorization predictions. A new factorization test has been performed by Ligeti, Luke and Wise [45]. Using the recent CLEO observation of $\mathrm{B}(\overline{B}^0 \to D^{*+}\pi^+\pi^-\pi^-\pi^0) = (1.72 \pm 0.14 \pm 0.24)\%$ [46], they compare the 4π spectrum in $B \to D^*$ decays to $\tau^- \to \nu\pi^+\pi^-\pi^-\pi^0$ data. Applying the factorization hypothesis, they find good agreement over the full accessible range up to $m^2_{4\pi} < 2.9\,\mathrm{GeV}^2$. This test, however, could be rendered invalid should $B \to D^*4\pi$ decays receive additional contributions from other decay diagrams. CLEO studied this issue by searching for the related decay mode $\overline{B}^0 \to D^{*0}\pi^+\pi^+\pi^-\pi^-$, which could proceed via D^{**} production, or through an internal spectator decay. They find a branching ratio for this mode of $(0.30 \pm 0.07 \pm 0.06)\%$ [47] and observe a large $D^{**} \to D^{*0}\pi^+$ component. This would invalidate the LLW factorization test, but when CLEO restricted their study to the q^2 range covered by the τ decays, *i.e.*, $m^2_{4\pi} < 2.9\,\mathrm{GeV}^2$, they find that there is almost no contribution to this part of the 4 pion spectrum (90 % C.L.)

$$\frac{\Gamma(\overline{B}^0 \to D^{*0}\pi^+\pi^-\pi^+\pi^-)}{\Gamma(\overline{B}^0 \to D^{*+}\pi^+\pi^-\pi^+\pi^0)} < 0.13 \qquad (14)$$

and hence the LLW factorization test remains valid.

Most hadronic decays of B mesons can be described by external and internal spectator decay diagrams. For charged B meson decays, these two amplitudes interfere, while for neutral B mesons they lead to separate final states. Two phenomenological parameters, a_1 and a_2, are introduced to absorb non-perturbative contributions to the external and internal spectator decay amplitudes, respectively. These parameters are expected to be process dependent [40], but current experimental data can be described with universal values $a_1 \approx 1.1$ and $a_2 \approx 0.25$.

For decays via the internal spectator process, the quarks from the virtual W decay must match the color of the quarks in the decaying hadron. The amplitude for this process is therefore suppressed compared to external spectator processes. In the decays of charm mesons, the effect of this color suppression is obscured by effects of final state interactions, or reduced by non-factorizable contributions. Color suppression is, however, believed to be operative in the B meson system. Until recently, the $B \to$ charmonium transitions were the only identified color-suppressed B decays. CLEO and Belle have now reported the observation of neutral B mesons decaying to $D^{(*)0}\pi^0$ final states [48], [49]. The CLEO result is

$$\mathrm{B}(\overline{B}^0 \to D^0\pi^0) = (2.74^{+0.36}_{-0.32} \pm 0.55) \times 10^{-4} \qquad (15)$$

and

$$\mathrm{B}(\overline{B}^0 \to D^{*0}\pi^0) = (2.20^{+0.59}_{-0.52} \pm 0.79) \times 10^{-4} \,. \qquad (16)$$

Combining these results with previous measurements of other $B \to D^{(*)}\pi$ final states, it is possible to extract the strong interaction phase δ_I between the isospin 1/2 and 3/2 amplitudes in the $D\pi$ and $D^*\pi$ final states. CLEO finds $\cos\delta_I = 0.89 \pm 0.08$ and $\cos\delta_I = 0.89 \pm 0.08$, respectively [48].

Comparing these results to models of hadronic B decays allows us to estimate $|a_2|_{B\to D^{(*)0}\pi^0} \approx 0.4$. This is significantly larger than the values for a_2 obtained from $B \to$ charmonium and charged B decays. The expected process dependence of a_2 mentioned above begins to show.

In summary, experimental results on exclusive B decay match 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. First indications of final state interactions and other strong interaction effects are beginning to emerge.

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 both semileptonic and hadronic $b \to u$ decays that are suppressed at leading order 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.

Over the past two years, many rare B-meson decays have been observed by BABAR, Belle and CLEO. The results are in general consistent between the three experiments and confirm the larger than expected rate for gluonic penguin decays such as $B \to K\pi$. No evidence for direct CP violation has been found in these decay modes. BABAR reports the first measurement of $B^0 \to D_s^+ \pi^-$, a $b \to u$ transition with the virtual W boson hadronizing as a D_s meson. Their result is $(3.1 \pm 1.0 \pm 1.0) \times 10^{-5}$ [50].

Electromagnetic penguin decays: The observation of the decay $B \to K^*(892)\gamma$, reported in 1993 by the CLEO experiment, provided first evidence for the one-loop penguin diagram [52]. Using larger data samples, CLEO, Belle and BABAR have updated this analysis and have added several new decay modes such as $B \to K_2^*(1430)\gamma$. So far no evidence for the decays $B \to \rho\gamma$ and $B \to \omega\gamma$ has been found. The current upper limit for the ratio $\mathrm{B}(B \to (\rho/\omega)\gamma)/\mathrm{B}(B \to K^*\gamma)$ is 0.32 at 90% CL. The limit on the ratio of branching fractions implies that $|V_{td}/V_{ts}| < 0.75$ at 90% CL.

The observed branching fractions were used to constrain a large class of Standard Model extensions [53]. 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. The current PDG average of the CLEO [54] and the Belle [58] measurements for the B meson is

$$\mathrm{B}(b \to s\gamma) \;=\; (3.3 \pm 0.4) \times 10^{-4}. \qquad (17)$$

Consistent results have been reported by ALEPH for b–hadrons produced at the Z^0.

The measured branching fraction can be compared to recent theoretical calculations by Chetyrkin, Misiak, Munz and by Kagan and Neubert which predict [55–57]

$$\mathrm{B}(b \to s\gamma) \; = \; (3.29 \pm 0.33) \times 10^{-4} \, . \qquad (18)$$

In addition, CLEO has measured the inclusive photon energy spectrum. Analyzing the shape of the spectrum they obtained the first and second moment for photon energies above 2 GeV:

$$< E_\gamma >= 2.346 \pm 0.032 \pm 0.011 \text{ GeV} \qquad (19)$$

and

$$< E_\gamma^2 > - < E_\gamma >^2 = 0.0226 \pm 0.0066 \pm 0.0020 \text{ GeV}^2 \, . \qquad (20)$$

These results can be used to extract non-perturbative HQET parameters that are needed for the determination of the CKM matrix element V_{ub}.

Additional information on flavor changing neutral current processes can be obtained from $B \to X_s \ell^+ \ell^-$ decays. Belle has reported [59] the first observation of such a decay and found

$$\mathrm{B}(B \to K \ell^+ \ell^-) \; = \; (0.75^{+0.25}_{-0.21} \pm 0.06) \times 10^{-6} \, . \qquad (21)$$

With a similarly sized dataset, BABAR [60] finds

$$\mathrm{B}(B \to K \ell^+ \ell^-) \; < \; 0.60 \times 10^{-6} \; (90\% \text{ CL}) \, . \qquad (22)$$

Both are consistent with Standard Model expectations.

Summary and Outlook: The study of B mesons continues to be one of the most productive fields in particle physics. CP violation has been observed for the first time outside the kaon system. Many hadronic $b \to u$ transitions and gluonic penguin decays have been observed, and the emerging pattern is still full of surprises. The coming years look equally promising. Each of the B-factory experiments, Belle and BABAR, will soon have accumulated data samples corresponding to 100 fb^{-1}. Run II at Fermilab has begun and new results from CDF and D0 can be expected soon. These experiments promise a rich spectrum of rare and precision measurements that have the potential to affect fundamentally our understanding of the Standard Model and CP-violating phenomena.

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