PRODUCTION AND DECAY OF b-FLAVORED HADRONS

Updated February 2006 by Y. Kwon (Yonsei U., Seoul, Korea) and G. Punzi (INFN, Pisa, Italy).

The b quark belongs to the third generation of quarks and is a weak doublet partner of the t quark. The existence of the third generation quark doublet was proposed in 1973 by Kobayashi and Maskawa [1] in their model of the quark mixing matrix ("CKM" matrix). In this model, the CP violation can be explained within the Standard Model (SM) by an irreducible phase of the 3×3 unitary matrix. Since b quark is the lighter element of the third generation quark doublet, the decay of b-flavored hadrons should occur via generation-changing processes through this matrix. Because of this and the CKM matrix being close to a 3×3 unit matrix, many interesting features such as loop and box diagrams, $B^0_{(s)}\overline{B}^0_{(s)}$ mixing, as well as the CP violations, can be observed in the weak decays of b-flavored hadrons.

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 [2,3]. The measurement of the CP-violation parameter $\sin 2\beta (= \sin 2\phi_1)$ [4] marks the culmination of a very significant experimental and theoretical program that started in 1973 [1]. Other recent developments in the physics of B mesons include new results on penguin decays, rare hadronic decays where improved measurements on nonstrange B have been supplemented by first measurements on strange B, improved limits on B^0_s mixing [5], as well as new determinations of the CKM matrix elements V_{cb} and V_{ub} [6], and of angles α and γ of the unitarity triangle.

The structure of this mini-review is organized as follows. First, we briefly update the results on b quark production and discuss the spectroscopy and the lifetimes of b-flavored hadrons. Then after a brief description of basic properties of B meson decays, we give a short description of the experimental results on CP violation in B meson decays. More details about formalism and implications of CP violations are described in a

CITATION: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL: http://pdg.lbl.gov)

separate mini-review [7] in this *Review*. This review closes with a description and update on hadronic and rare decays of B mesons. There are separate mini-reviews on the $B\overline{B}$ mixing [5] and on the extraction of the CKM matrix elements V_{cb} and V_{ub} from B decays [6] in this *Review*.

Production and spectroscopy: Elementary particles are characterized by their masses, lifetimes, and internal quantum numbers. The bound states with a $\overline{b}$ antiquark and a u, d , s, or c quark are referred to as the B_u (B^+), B_d (B^0), B_s (B_s^0), and B_c (B_c^+) 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^{**}. Although the b quark was discovered in a fixed-target experiment at Fermilab in 1977, most of the experimental information on b-flavored hadrons has come from colliding-beam machines. Experimental studies of b decay have been performed at the $\Upsilon(4S)$ resonance near production threshold, as well as at higher energies in proton-antiproton collisions and Z decays. Currently, there is no experiment running at Z resonance; in a year or two, experiments at LHC with proton-proton collisions will start producing b-flavored hadrons. The bb production cross-section at the Z and $\Upsilon(4S)$ resonances are about 6.6 nb and 1.1 nb, respectively. High-energy $p\overline{p}$ collisions at the Tevatron produce b-flavored hadrons of all species with very large cross-section ($\sigma_{bb} \sim 50\mu b$), but due to the large backgrounds, only a selection of modes can be studied that are easier to trigger and reconstruct, notably the final states with leptons, and the exclusive modes into all charged particles.

Large samples of a rich variety of modes of the B^0 and B^+ mesons have been collected by the e^+e^- collider detectors running at $\Upsilon(4S)$ ("B-Factories"). As of this writing, BABAR and Belle have accumulated approximately 300 fb^{-1} and 500 fb^{-1}, respectively. The $\Upsilon(4S)$ resonance decays only to $B^0\overline{B}^0$ and B^+B^- pairs; the current experimental limit for non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is less than 4% at the 95% confidence level (CL) [8].

For quantitative studies of B decays, the initial composition of the data sample must be known. In particular, the ratio f_+/f_0 of charged to neutral $\Upsilon(4S)$ decays is crucial to calculate the decay branching fractions for B-factory experiments. CLEO and BABAR have measured the ratio $(f_+/f_0)(\tau_+/\tau_0)$ with exclusive $B \to \psi K^{(*)}$ [9,10] and $B \to D^*\ell\nu$ [11] decays, where τ_+/τ_0 is the B^+/B^0 lifetime ratio (see next section). By using the world-average value of τ_+ and τ_0 Belle also extracted the value of f_+/f_0 [12]. Using the current average of τ_+/τ_0, the average becomes $f_+/f_0 = 1.020 \pm 0.034$ [13]. 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: our fit of CLEO, ARGUS, and CDF measurements yields $m(B^0) = 5279.4 \pm 0.5$ MeV/c^2, $m(B^+) = 5279.0 \pm 0.5$ MeV/c^2, and $m(B^0) - m(B^+) = 0.33 \pm 0.28$ MeV/c^2.

In high-energy collisions, the produced $\bar{b}$ (or b) quarks can hadronize as B^0, B^+, B_s^0, and B_c^+ mesons (or their antiparticles), or as baryons containing $\bar{b}$ (or b) quarks; to date, all mesons, the Λ_b baryon, and various excitations have been established. Table 1 shows the fractions f_d, f_u, f_s, and $f_{\rm baryon}$ of B^0, B^+, B_s^0, and b baryons in an unbiased sample of weakly decaying b hadrons produced at the Z resonance and in $p\overline{p}$ collisions [13]. A detailed account can be found elsewhere in this *Review* [5]. 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 momentum distributions of the b–quark in these processes. With the availability of sizeable samples of B_s^0 mesons and Λ_b baryons at $p\overline{p}$ colliders, the knowledge of these fractions has also become an important limiting factor in the determination of their branching fractions.

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

b hadron	Fraction [%]
B^+, B^0	39.8 ± 1.0
B^0_s	10.4 ± 1.4
b baryons	9.9 ± 1.7

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 at the MeV level. The recent measurement by CDF [17] yields: $m(B^0_s) = 5366.01 \pm 0.73 \pm 0.33$ MeV/c^2 and $m(\Lambda_b) = 5619.7 \pm 1.2 \pm 1.2$ MeV/c^2.

Clear evidence for the B^+_c, the last weakly decaying bottom meson, has been obtained by both CDF and D0 in the semileptonic mode [18]; CDF also observes the fully reconstructed mode $B^+_c \to J/\Psi\pi^+$, which allows an accurate mass measurement: $6285.7 \pm 5 \pm 1.2$ MeV/c^2 [19].

First indications of Ξ_b production have been presented by the LEP Collaborations [21,22].

Excited B-meson states have been observed by CLEO, LEP, CUSB, D0, and CDF. The current world average of the B^*–B mass difference is 45.78 ± 0.35 MeV/c^2. Evidence for B^{**} production has been presented by the LEP and CDF experiments [23], as a broad resonance in the mass of an inclusively reconstructed bottom hadron candidate combined with a charged pion from the primary vertex. Preliminary results with exclusive modes have been obtained by D0, allowing separation of the narrow states, B_1 and B^*_2, with masses $m(B_1) = 5724 \pm 4 \pm 7$MeV/$c^2$ and $m(B^*_2) - m(B_1) = 23.6 \pm 7.7 \pm 3.9$ MeV/c^2 [24].

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 $B_s^0\overline{B}_s^0$ 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 should be significantly smaller, of order 10% or less [25]. For the b system we expect

$$\tau(B^+) \geq \tau(B^0) \approx \tau(B_s^0) > \tau(\Lambda_b^0) \gg \tau(B_c^+) . \qquad (1)$$

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, advanced algorithms based on impact parameter or decay length measurements exploiting the potential of silicon vertex detectors resulted in improvement of lifetime measurements. 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 Heavy Flavor Averaging Group (HFAG) [13]. A detailed description of the procedures and the treatment of correlated and uncorrelated errors can be found in [26]. The asymmetric B factories are now making significant contributions to the B^+ and B^0 lifetime measurements. Their use of fully–reconstructed B decays yield measurements with much reduced statistical and systematic uncertainties. The measurements are free, for example, from systematics associated with modelling of fragmentation. The new world average b-hadron lifetimes are summarized in Table 2.

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

Particle	Lifetime [ps]
B^+	1.643 ± 0.010
B^0	1.527 ± 0.008
B^0_s	1.454 ± 0.040
B^+_c	0.469 ± 0.065
Λ_b	1.288 ± 0.065
Ξ_b mixture	$1.39^{+0.34}_{-0.28}$
b baryon mixture	1.242 ± 0.046
b hadron mixture	1.568 ± 0.009

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

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.076 \pm 0.008\,, \ \frac{\tau_{B^0_s}}{\tau_{B^0}} = 0.914 \pm 0.030\,,$$

$$\frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.844 \pm 0.043\,,$$

while theory makes the following predictions [27,28]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.06 \pm 0.02\ , \quad \frac{\tau_{B^0_s}}{\tau_{B^0}} = 1.00 \pm 0.01\ , \quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.86 \sim 0.95\ .$$

The short B_c^+ lifetime has been predicted correctly. The long-standing discrepancy between Λ_b-baryon lifetime and its predicted value has now been reduced by updated calculations that include higher-order effects [28]. Conversely, the ratio of B_s to B^0 lifetimes now exhibits an almost 3-sigma deviation from expectations.

Similar to the kaon system, neutral B mesons contain short- and long-lived components. The SM predicts that the lifetime difference is significantly smaller. The most stringent limit on the lifetime difference of neutral B_d mesons is recently obtained by BABAR: $-0.156 < \Delta\Gamma_d/\Gamma_d < 0.042$ at 90% CL [29], where $\Delta\Gamma_d \equiv \Gamma_H - \Gamma_L$ with $\Gamma_H(\Gamma_L)$ being the decay width of the heavier (lighter) B_d meson. They measure the time-dependence of $\Upsilon(4S)$ decays where one neutral B is fully reconstructed and the other B is identified as being either B^0 or $\overline{B}^0$. In this analysis, possible violations in CP, T, and CPT are fully considered.

The lifetime difference for B_s^0 currently predicted by the Standard Model is $\Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.05$ [30]. The experimental knowledge has improved due to new measurements from CDF and D0, based on angular analysis of the mode $B_s \to J/\psi\phi$ to separate CP even and CP odd components. By appropriately combining all available measurements, the HFAG group obtains a world average: $\Delta\Gamma_s/\Gamma_s = 0.31^{+0.10}_{-0.11}$; the quoted uncertainties are, however, non-gaussian, and a better representation of the current uncertainty is given by the 95% CL confidence interval: $0.01 < \Delta\Gamma_s/\Gamma_s < 0.59$ [13] that barely excludes zero. The measurement includes constraints from flavor-specific measurements, but they have only a small effect. The assumption of $\Gamma_s = \Gamma_d$ is no longer used, due to the 2.9 σ difference between their current estimates.

B meson decay properties: B^+ and B^0 mesons are the lightest elements of the b-flavored hadrons, hence they decay via weak interactions. Since the mass of a b-quark is much larger than its partner quark (d or u), B meson decays are mostly described by the decay of the b quark ("spectator model"). The dominant decay mode of a b-quark is $b \to cW^*$, where the virtual W^* eventually materializes either into a pair of leptons, $\ell\nu$ ("semileptonic decay"), or into a pair of quarks which then hadronizes. The decays in which the spectator quark combines with one of the quarks from W^* are suppressed because the colors of the quarks from different sources must match ("color-suppression").

Couplings of quarks to the W boson are described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. 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 CKM matrix. In the Standard Model (SM) of three generations, the CKM matrix is parameterized by three real parameters and one complex phase. This complex phase can become a source of CP violations in B meson decays. A more detailed discussion of the

CKM matrix and CP violation can be found elsewhere in this *Review* [7,31].

Semileptonic B decays $B \to X_c \ell \nu$ and $B \to X_u \ell \nu$ provide an excellent laboratory to measure CKM elements $|V_{cb}|$ and $|V_{ub}|$ respectively, because the strong interaction effects are much simplified due to the two leptons in the final state. Both exclusive decays and inclusive decays can be used, and the nature of uncertainties are quite complimentary. For exclusive decay analysis, a knowledge about the form factors for the exclusive hadronic system $X_{c(u)}$ is required. For inclusive analysis, it is usually required to restrict the available phase-space of the decay products to suppress backgrounds; subsequently uncertainties are introduced in the extrapolation to the full phase-space. Moreover, restriction to a small corner of the phase-space may result in breakdown of the operator product expansion scheme, thus making theoretical calculations unreliable. A more detailed discussion of the B semileptonic decays and extraction of $|V_{cb}|$ and $|V_{ub}|$ are described elsewhere in this *Review* [6].

On the other hand, hadronic decays of B are complicated because of strong interaction effects caused by the surrounding cloud of light quarks and gluons. While this complicates the extraction of CKM matrix elements, it also provides a great opportunity to study perturbative and non-perturbative QCD, hadronization, and Final State Interaction (FSI) effects, *etc.*

Other (non-spectator) decay processes include W-exchange and annihilation decays, both of which occur at tree-level processes. Higher-order loop-induced flavor-changing neutral current (FCNC) decay processes ("Penguin decays") are also available. In the Standard Model, these decays are much suppressed in comparison to the spectator decays. Penguin decays are experimentally established by observations of $B \to K^* \gamma$ and recently $B \to K^{(*)} \ell^+ \ell^-$. Some observed decay modes such as $B^0 \to D_s^- K^+$ may be interpreted as a W-exchange process.

There has been so far no experimental evidence for pure-annihilation decays of B mesons. Measurement of the branching fractions of these modes would be very useful to reduce uncertainty in the predictions for many other modes, as the contribution of annihilation diagrams is very difficult to predict with the current theoretical tools. Limits on these modes have recently improved and are now an order of magnitude above typical theoretical predictions: $\mathcal{B}(B_d^0 \to K^+K^-) < 3.7 \times 10^{-7}$ [14] and $\mathcal{B}(B_s^0 \to \pi^+\pi^-) < 1.7 \times 10^{-6}$ [16,13].

Experimental results on CP violation in B decays: The determination of all the parameters of the CKM matrix is required to fully define the SM, and is central to the experimental program in heavy-flavor physics. In the framework of the SM, 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

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

The interior angles of the triangle can be expressed in terms of the CKM elements

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

$$\beta = \phi_1 = arg(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*})\,,$$

$$\gamma = \phi_3 = arg(-\frac{V_{cd}V_{cb}^*}{V_{ud}V_{ub}^*})\,.$$

The most precise measurements of the angle β have come from the two energy-asymmetric B-factories running at $\Upsilon(4S)$, KEKB and PEP-II, by analyzing time-dependent CP asymmetries in $b \to c\bar{c}s$ decay modes including $B \to J/\psi K_S$. Since the B mesons receive very little boost in the $\Upsilon(4S)$ rest frame, asymmetric beam energies are required to improve the precision of time-dependence measurement. At KEKB, for example, the boost is $\beta\gamma = 0.43$, and the typical B meson decay length is dilated from $\approx 20\ \mu m$ to $\approx 200\ \mu m$. PEP-II uses a slightly larger boost, $\beta\gamma = 0.55$.

In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{CP} f_{\rm tag}$, in which one of the B mesons decays at time t_{CP} to f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependence given by [7]

$$\mathcal{P}^q_{f_{CP}}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 + q\cdot\{S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\}\right],$$

where τ is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, and $\Delta t = t_{CP} - t_{\rm tag}$. The parameter q is determined by identifying the b-quark flavor of the accompanying B meson ("flavor tagging") using inclusive features of the charged particles in $f_{\rm tag}$. For instance, $q = +1(-1)$ when the tagging B meson is a B^0 ($\overline{B}^0$). The CP-violating parameters S and C are expressed as

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S = \frac{2Im\lambda}{1+|\lambda|^2},$$

where λ is a complex parameter that depends on both B^0-$\overline{B}^0$ mixing and on the amplitudes for B^0 and $\overline{B}^0$ decay to f_{CP}. In the SM, to a good approximation, $|\lambda|$ is equal to the absolute value of the ratio of the $\overline{B}^0$ to B^0 decay amplitudes. In the absence of direct CP violation, $|\lambda| = 1$. For $b \to c\bar{c}s$ transition, the SM predicts $S = -\xi \sin 2\beta$, where $\xi = +1(-1)$ for CP-even (-odd) final states, and $C = 0$.

In the summer of 2001, both BABAR [2] and Belle [3] reported first significant non-zero measurements of $\sin 2\beta$, thereby establishing CP violation in the B^0 meson decays. Both experiments have updated their results recently. Using a data sample of 227 million $B\overline{B}$ pairs, BABAR [40] obtained $\sin 2\beta = 0.722 \pm 0.040 \pm 0.023$, while with 386 million $B\overline{B}$ pairs, Belle [41] reported $\sin 2\beta = 0.652 \pm 0.039 \pm 0.020$ in $B^0 \to J/\psi K^0$ decays. Averaging the latest results from the two experiments, HFAG finds [13] $\sin 2\beta = \sin 2\phi_1 = 0.685 \pm 0.032$. Including the measurements from higher energy collider experiments, the average becomes

$$\sin 2\beta = \sin 2\phi_1 = 0.687 \pm 0.032.$$

The average for C is 0.026 ± 0.041 which is consistent with zero. These values are consistent with CKM expectations.

From the average of $\sin 2\beta$ above, we obtain the following two solutions for β (in $[0, \pi]$): $\beta = (21.7^{+1.3}_{-1.2})^\circ$ or $\beta = (68.3^{+1.2}_{-1.3})^\circ$. This ambiguity may be resolved by measuring time-dependent CP asymmetry in $B^0 \to \overline{D}^0 h^0$ decays, where $\overline{D}^0$ decays to a CP-eigenstate, *e.g.* $K^0_S\pi^+\pi^-$. Using a sample of 386 million $B\overline{B}$ pairs, Belle has performed a Dalitz plot analysis of $\overline{D}^0 \to K^0_S\pi^+\pi^-$ for a time-dependent CP asymmetry in $B^0 \to \overline{D}^0 h^0$ (where $h = \pi^0$ or η), and obtained $\beta = (16) \pm 21 \pm 12°$. The 95% CL region is $-32° < \beta < 62°$, which disfavors the $\beta = 68.3°$ solution.

Charmless B decays mediated by the $b \to s$ penguin transition are potentially sensitive to new CP-violating phases from physics beyond the SM [42]. In the SM, measurement of S in the $b \to s\bar{s}s$ transition should yield approximately the same value ($-\xi \sin 2\beta$) as in the $b \to c\bar{c}s$ modes. Both BABAR and Belle measured S for $b \to s\bar{s}s$ modes, including $B \to \eta' K^0_S$ and ϕK^0_S. The "naïve" average value of effective $\sin 2\beta (\equiv \sin 2\beta_{\rm eff})$ for $b \to sq\bar{q}$ transitions (the cases where $q = s$ are believed to be mostly penguin, but others may have significant non-penguin contributions) calculated by HFAG is 0.50 ± 0.06 where the error is dominantly statistical. Since each mode can have different uncertainties in the SM, this "naïve" average should not be taken too seriously. At this moment, the comparison of $S_{sq\bar{q}}$ with $\sin 2\beta$ obtained from $b \to c\bar{c}s$ is inconclusive. The largest deviation from $b \to c\bar{c}s$ result ($\sin 2\beta = 0.687$) comes from $\eta' K^0$. With a sample of 232 million $B\overline{B}$ pairs, BABAR measures $-\xi S_{\eta' K^0} = 0.36 \pm 0.13 \pm 0.03$, while Belle measures $-\xi S_{\eta' K^0} = 0.62 \pm 0.12 \pm 0.04$, with a sample of 386 million $B\overline{B}$ pairs. The HFAG average of the two is 0.50 ± 0.09. A B_s mode mediated by the $b \to s\bar{s}s$ transition has also been observed: $B_s \to \phi\phi$. Its measured branching fraction: $\mathcal{B}(B_s \to \phi\phi) = (14^{+6}_{-5} \pm 6) \times 10^{-6}$ [74], is in agreement with SM expectations at the current level of precision.

The $b \to c\bar{c}d$ transition can occur via a $b \to c$ tree or a $b \to d$ penguin process. The weak phase of the penguin amplitude relative to that of the tree contains the information of CP-violating phase other than that from $B^0\overline{B}^0$ mixing. Both Belle and BABAR investigated this using the final states $J/\psi\pi^0$, $D^{*+}D^{*-}$, and $D^{*\pm}D^{\mp}$. The results in all these modes are consistent with being dominated by tree amplitude, and with the $\sin 2\beta$ measured from $b \to c\bar{c}s$ modes.

Experimental work on the determination of the other two angles, α and γ of the unitarity triangle, is also underway. Much larger data samples will be needed to obtain precision results and to challenge the SM. Information on $\sin 2\alpha$ can be extracted from time-dependent CP asymmetry measurements of $b \to u\bar{u}d$ processes, such as $B^0 \to \pi^+\pi^-$, $\rho^+\rho^-$, and $\rho^\pm\pi^\mp$ decays, following a procedure similar to the one outlined above. Unfortunately, these decays suffer from fairly small branching fractions ($\mathcal{O}(10^{-6})$) and sizeable contributions from penguin diagrams that complicate the extraction of the CP phases. Because of this, the time-dependent asymmetry in $B \to \pi^+\pi^-$, for example, will not be proportional to $\sin\alpha$, but to $\sin 2\alpha_{\rm eff}$, with an unknown correction to α.

Despite these difficulties, attempts to measure CP asymmetries in the $b \to u\bar{u}d$ modes have been reported. For the $B^0 \to \pi^+\pi^-$ mode, BABAR [43] extracts $S(= \sqrt{1-C^2} \times \sin 2\alpha_{\rm eff}) = -0.30 \pm 0.17 \pm 0.03$, using 227 million $B\overline{B}$ pairs, and Belle [44] finds $S = -0.67 \pm 0.16 \pm 0.16$ with 275 million events. The contribution from direct CP violation in the $B \to \pi^+\pi^-$ decay shows up as a nonzero amplitude C. Both experiments have determined C simultaneously with S. BABAR finds $C = -0.09 \pm 0.15 \pm 0.04$, while Belle measures $C = -0.56 \pm 0.12 \pm 0.06$, by which Belle claims an evidence of direct CP violation at a significance of 4.0σ. The difference of BaBar and Belle corresponds to 2.3σ discrepancy. Extracting the angle α from $\pi^+\pi^-$ is not easy because of large branching fraction of $B^0 \to \pi^0\pi^0$ [45,46], resulting in a large uncertainty in the isospin analysis.

On the other hand, BABAR searched for $B^0 \to \rho^0\rho^0$ and finds that the branching fraction is less than 1.1×10^{-6} (90% CL) [47], which is much smaller than the isospin-related modes. Therefore, the penguin pollution in the $B^0 \to \rho^+\rho^-$ is small, making extraction of α easier than the $\pi^+\pi^-$ mode. BABAR [48] extracts $S = -0.33 \pm 0.24^{+0.08}_{-0.14}$ for the $\rho^+\rho^-$ mode, while Belle [49] obtains $S = 0.08 \pm 0.41 \pm 0.09$. The C value is consistent with zero in both analyses. Using the upper limit on $\mathcal{B}(B^0 \to \rho^+\rho^-)$ determined by BABAR, isospin analyses are performed for both results to constrain α: BABAR obtains $\alpha = (100 \pm 13)^\circ$, while Belle obtains $\alpha = (88 \pm 17)^\circ$. BABAR uses the combined average for $\mathcal{B}(B^+ \to \rho^+\rho^0)$; Belle uses the combined averages for both $\mathcal{B}(B^0 \to \rho^+\rho^-)$ and

$\mathcal{B}(B^+ \to \rho^+\rho^0)$. In both analyses, electroweak penguins and possible $I = 1$ amplitudes are ignored.

CP asymmetry in $B^0 \to \rho^\pm\pi^\mp$ mode is also studied to extract the angle α. BABAR used a Dalitz plot analysis for $\pi^+\pi^-\pi^0$ [50] while Belle used a quasi 2-body model [51]. In both analyses, the S value is consistent with zero, but the HFAG average of the C value is 0.31 ± 0.10 which is away from zero with a significance of 3.4σ.

Several methods have been suggested to measure the third angle, $\gamma \approx \arg(V_{ub})$ [52]. However, they require very large data samples (such as for $B \to DK$), measurements of B_s^0 decays, or suffer from large theoretical uncertainties, rendering γ particularly difficult to measure.

The decay amplitudes for $B^+ \to D^{(*)0}K^{(*)+}$ and $B^+ \to \overline{D}^{(*)0}K^{(*)+}$ can interfere if the $D^{(*)0}$ and $\overline{D}^{(*)0}$ decay to a common final state, for example $D^{*0} \to D^0\pi^0$ and $D^0 \to K_S^0\pi^+\pi^-$. Since the Cabibbo-suppressed $B^+ \to D^{(*)0}K^{(*)+}$ amplitude involves V_{ub}, the interference is sensitive to the angle γ. There have been several methods suggested to extract γ by using this interference, including those where the $D^{(*)0}$ is reconstructed as a CP eigenstate (GLW) [53], in a suppressed final state (ADS) [54]. Analyzing the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot is another method to exploit this interference. [55]

Both BABAR [56] and Belle [57] applied GLW and ADS methods to obtain CP asymmetries and related parameters. At the moment, the results from Dalitz plot analyses give tightest restriction on γ. Using 275 million $B\overline{B}$ pairs, Belle measured $\gamma = (68^{+14}_{-15} \pm 13 \pm 11)^\circ$ by combining DK^+ and D^*K^+ modes [58]. BABAR measured, with a sample of 227 million events, $\gamma = (67 \pm 28 \pm 13 \pm 11)^\circ$ by combining DK^+, D^*K^+ and DK^{*+} modes [59]. The attempts to combine all these measurements for γ have been made by the CKMfitter and UTFit groups [60].

The Cabibbo-favoured $B^0 \to D^{(*)-}\pi^+$ amplitude can have interference with the doubly Cabibbo-suppressed amplitude of $\overline{B}^0 \to D^{(*)-}\pi^+$. The relative weak phase between these two amplitudes is γ and, when combined with the $B^0\overline{B}^0$ mixing phase, the total phase difference is $-(2\beta + \gamma)$. Therefore $B^0 \to$

$D^{(*)\pm}\pi^{\mp}$ decays can provide sensitivity to γ. The interpretation of the observables in terms of unitarity angles requires external input on the ratio of magnitude of the two amplitudes. Due to the disparate strength of the two interfering amplitudes, CP asymmetry is expected to be small, hence the possible occurrence of CP violation on the tag side may become an important obstacle. Both Belle and BABAR have measured the CP-violation parameters for $D^{\pm}\pi^{\mp}$ and $D^{*\pm}\pi^{\mp}$ modes. For the $D^{*\pm}\pi^{\mp}$ mode, both full and partial reconstruction techniques were used by both experiments. BABAR also studied $D^{\pm}\rho^{\mp}$ mode.

Hadronic B decays: The experimental results on hadronic B decays have steadily improved over the past years and the measurements have reached a 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 [61,62].

With a good neutral particle detection and hadron identification capabilities of B-factory detectors, a substantial fraction of hadronic B decay events can be fully reconstructed. Because of the kinematic constraint of $\Upsilon(4S)$, the energy sum of the final-state particles of a B meson decay is always equal to one half of the total energy in the center of mass frame. As a result, the two variables, ΔE (energy difference) and M_B (B candidate mass with a beam-energy constraint) are very effective to suppress combinatorial background both from $\Upsilon(4S)$

and $e^+e^- \to q\bar{q}$ continuum events. In particular, the energy-constraint in M_B improves the signal resolution by almost an order of magnitude.

Such a kinematically clean environment of B meson decays provides a very nice laboratory to search for new states. For instance, quark-level $b \to c\bar{c}s$ decays have been used to search for new charmonium and charm-strange mesons and study their properties in detail. In 2003, BABAR discovered a new narrow charm-strange state $D^*_{sJ}(2317)$ [63], and CLEO observed a similar state $D_{sJ}(2460)$ [64]. But the properties of these new states were largely unknown until Belle observed $B \to DD^*_{sJ}(2317)$ and $B \to DD_{sJ}(2460)$, which helped identify some quantum numbers of $D_{sJ}(2460)$ [65]. Further studies of $D^{(*)}_{sJ}$ meson productions in B decays have been made by Belle and BABAR. In particular, BABAR has observed $B \to D^*_{sJ}(2317)^+\overline{D}^{(*)}$ ($D^*_{sJ}(2317)^+ \to D^+_s\pi^0$) and $B \to D_{sJ}(2460)^+\overline{D}^{(*)}$ ($D_{sJ}(2460)^+ \to D^{*+}_s\pi^0$, $D^+_s\gamma$) decays. The angular analysis of $B \to D_{sJ}(2460)^+\overline{D}$ with $D_{sJ}(2460)^+ \to D^+_s\gamma$ supports the $J^P = 1^+$ assignment for $D_{sJ}(2460)$. With 152 million $B\overline{B}$ pairs, Belle studied the $\overline{B}^0 \to D^+_{sJ}K^-$ and $\overline{B}^0 \to D^-_{sJ}\pi^+$ decays. A significant signal for $\overline{B}^0 \to D^*_{sJ}(2317)^+K^-$ is observed with $\mathcal{B}(\overline{B}^0 \to D^*_{sJ}(2317)^+K^-) \times \mathcal{B}(D^*_{sJ}(2317)^+ \to D^+_s\pi^0) = (5.3^{+1.5}_{-1.3} \pm 0.7 \pm 1.4) \times 10^{-5}$.

Studies have been made to understand the properties of the new charmonium-like exotic particle, $X(3872)$, which was discovered by Belle [66] and later confirmed by other experiments [67]. In addition, more charmonium-like exotic particles have been observed in B decays.

Belle has searched for possible decays to $D\overline{D}$ and $D^0\overline{D}^0\pi^0$ of $X(3872)$ and set upper limits for $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D\overline{D})$ and $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D^0\overline{D}^0\pi^0)$ [68]. In a related analysis [68], Belle observed the $B^+ \to \psi(3770)K^+$ where $\psi(3770)$ is reconstructed in $D^0\overline{D}^0$ and D^+D^- channels. The obtained branching fraction is $\mathcal{B}(B^+ \to \psi(3770)K^+) = (0.48 \pm 0.11 \pm 0.07) \times 10^{-3}$.

BABAR has searched for $X(3872) \to J/\psi\eta$ and set upper limits for $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to J/\psi\eta)$ [69].

In a related analysis [69], BABAR observed the $B \to J/\psi\eta K$ decays. The obtained branching fractions are $\mathcal{B}(B^+ \to J/\psi\eta K^+) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}$ and $\mathcal{B}(B^0 \to J/\psi\eta K^0_S) = (8.4 \pm 2.6 \pm 2.7) \times 10^{-5}$. BABAR also made a search for a charged partner of the $X(3872)$ in $B \to X^- K$ decays and set upper limits on product branching fractions, ruling out the isovector-X hypothesis [70].

More charmonium-like exotic particles have been observed in B decays. Belle has observed a near-threshold enhancement in the $\omega J/\psi$ invariant mass for $B \to K\omega J/\psi$ decays [71]. If treated as an S-wave Breit-Wigner resonance, the mass is $(3943 \pm 11 \pm 13)$ MeV/c^2 and the total width is $87 \pm 22 \pm 26$ MeV. BABAR has studied the $B \to J/\psi\pi^+\pi^- K$ and, in particular, the $J/\psi\pi^+\pi^-$ mass distribution in a region above the $X(3872)$ [72]. They found an excess of $J/\psi\pi^+\pi^-$ events with a mass just above 4.2 GeV/c^2, which is consistent with $Y(4260)$ that was observed by BABAR in ISR events [73].

There have been nearly 50 papers on hadronic B decays to open-charm and charmonium final states published since 2004. These results are nicely summarized in a recent report by HFAG [13].

Rare B decays: All B-meson decays that do not occur through the usual $b \to c$ transition are usually called 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 $b \to s$ processes such as electroweak and gluonic penguin decays.

Charmless B meson decays into two-body hadronic final states such as $B \to \pi\pi$ and $K\pi$ are experimentally clean, and provide good opportunities to probe new physics and search for indirect and direct CP violations. The final state particles in these decays tend to have larger momenta than average B decay products, therefore the event environment is cleaner than $b \to c$ decays. Branching fractions are typically around 10^{-5}, for exclusive channels. Over the past years, many such modes have been observed by BABAR, Belle, and CLEO. More recently, comparable samples of the modes with all charged final particles have been reconstructed in $p\bar{p}$ collisions by CDF, by triggering on impact parameter of final particles. This also allowed to observe charmless decays of the B_s for the first time, in modes $B_s^0 \to \phi\phi$ [74] and $B_s^0 \to K^+K^-$ [15].

Because of relatively high-momenta for final state particles, the dominant source of background in e^+e^- collisions is $q\bar{q}$ continuum events, and sophisticated background suppression techniques exploiting the event shape variables are essential for these analyses. In hadron collisions, the dominant background comes from QCD or partially reconstructed heavy flavors, and is similarly suppressed by a combination of kinematical and isolation requirements. The results are in general consistent among the four experiments.

Recent additions to the list of observed two-body charmless hadronic decays include $B^+ \to \overline{K}^0 K^+$ and $B^0 \to K^0\overline{K}^0$. Analyzing a sample of 227 million $B\overline{B}$ pairs, BABAR measured $\mathcal{B}(B^+ \to K^0\overline{K}^0) = (1.19^{+0.40}_{-0.35} \pm 0.13) \times 10^{-6}$, and $\mathcal{B}(B^+ \to \overline{K}^0 K^+) = (1.5 \pm 0.5 \pm 0.1) \times 10^{-6}$, with significance of 4.5σ and 3.5σ, respectively [75]. Similarly, using a sample of 275 million $B\overline{B}$ pairs, Belle measured $\mathcal{B}(B^+ \to K^0\overline{K}^0) = (0.8 \pm 0.3 \pm 0.1) \times 10^{-6}$ and $\mathcal{B}(B^+ \to \overline{K}^0 K^+) = (1.0 \pm 0.4 \pm 0.1) \times 10^{-6}$ with significance of 3.5σ and 3.0σ, respectively [14]. These are evidences for hadronic $b \to d$ transitions.

Several rare decay modes such as $B^0 \to K^+\pi^-$ have contributions from both $b \to u$ tree and $b \to sg$ penguin diagram processes. If the size of each contribution is comparable to each other, the interference between them may cause direct CP violation which can show up as a charge asymmetry in time-independent decay rate measurement. Recently, both BABAR and Belle found evidences for direct CP violation in $B^0 \to K^+\pi^-$ decays [76]. Including the improved preliminary measurement from Belle [77], the new average for charge asymmetry in the $K^+\pi^-$ mode is -0.115 ± 0.018 [13]. Under SM assumptions, the observation of CP asymmetry in this mode requires asymmetries to exist in other modes at non-negligible levels. Examples are the isospin-related mode $B^+ \to K^+\pi^0$, which is expected to have a similar asymmetry, and the as yet unobserved mode $B_s \to K^-\pi^+$, where a large asymmetry is expected [78,79]. Their comparisons will be an important check of SM interpretation of the observed CP asymmetry.

There is a B^+ decay mode which also appears to indicate direct CP violation: $B^+ \to \rho^0 K^+$. By analyzing the Dalitz plot for $B^+ \to K^+\pi^-\pi^+$ decays using a sample of 386 million $B\overline{B}$ pairs, Belle measured the charge asymmetry for $B^+ \to \rho^0 K^+$ as $(30 \pm 11^{+11}_{-5})\%$ [80], which is different from zero with a significance of 3.9σ. In a similar analysis using a sample of 226 million $B\overline{B}$ events, BABAR measured the charge asymmetry of $\rho^0 K^+$ as $(32 \pm 13^{+10}_{-8})\%$ [81].

The fact that $B^0 \to \pi^+\pi^-$ can have interference between tree and penguin processes makes it difficult to extract a unitarity angle α from time-dependent CP asymmetry measurements. In order to extract α unambiguously, an isospin analysis has been suggested [82]. A crucial element for the isospin analysis is a flavor-specific measurement of $B^0 \to \pi^0\pi^0$ and $\overline{B}^0 \to \pi^0\pi^0$. Recently, both BABAR and Belle updated the measurements: $\mathcal{B}(B^0 \to \pi^+\pi^-) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}$ for Belle (with 275 million $B\overline{B}$ events) [46], and $\mathcal{B}(B^0 \to \pi^+\pi^-) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$ for BABAR (with 227 million events) [45]. Similarly, $B^0 \to \rho^0\rho^0$ plays a crucial role in extracting α from CP asymmetry measurements in $B^0 \to \rho^+\rho^-$. BABAR obtained a stringent upper limit on this mode: $\mathcal{B}(B^0 \to \rho^0\rho^0) < 1.1 \times 10^{-6}$ [84].

Since $B \to \rho\rho$ consists of two vector mesons in the final state, the CP eigenvalue of the final state depends on the longitudinal polarization fraction f_L for the decay. Therefore, a precise knowledge of f_L is crucial to extract CKM angle α. Both BABAR and Belle have observed $B^0 \to \rho^+\rho^-$ [48,49] and $B^+ \to \rho^+\rho^0$ [85] decays and measured their polarizations. The average value of f_L is: $f_L = 0.971^{+0.031}_{-0.030}$ for $\rho^+\rho^-$ and $0.97^{+0.05}_{-0.07}$ for $\rho^+\rho^0$ [13].

By analyzing the angular distributions of the B decays to two vector mesons, we can learn a lot about both weak- and strong-interaction dynamics in B decays. A detailed description of the angular analysis of B decays to two vector mesons can be found in a separate mini-review [86] in this *Review* .

The recently observed $B_s \to K^+K^-$ mode is related to $B^0 \to \pi^+\pi^-$ by U-spin symmetry, and is similary determined by a superposition of tree and penguin diagrams. Combining the observables from these two modes is another way of eliminating hadron uncertainties and extracting relevant CKM information [83].

The decay $B^0 \to D_s^+\pi^-$ proceeds via $b \to u$ tree diagram, where D_s is produced from the vertex of virtual W hadronization. Therefore, it is sensitive to $|V_{ub}|$, although actual extraction of $|V_{ub}|$ becomes obscured by unknown non-factorizable strong-interaction effects. Both Belle [87] and BABAR [88] found evidences for this mode, and the average branching fraction is $\mathcal{B}(B^0 \to D_s^+\pi^-) = (2.7 \pm 1.0) \times 10^{-5}$.

In the SM, the decay $B^+ \to D_s^{(*)+}\phi$ is expected to occur via a weak annihilation diagram, which is highly suppressed. As a result, this mode is very sensitive to new physics effects. Using a sample of 234 million $B\overline{B}$ pairs, BABAR obtained a much improved upper limit for the modes: $\mathcal{B}(B^+ \to D_s^+\phi) < 1.9 \times 10^{-6}$ and $\mathcal{B}(B^+ \to D_s^{*+}\phi) < 1.2 \times 10^{-5}$ [89].

Electroweak penguin decays:

More than a decade has passed since the CLEO experiment first observed an exclusive radiative $b \to s\gamma$ transition, $B \to K^*(892)\gamma$ [90], thus providing the first evidence for the one-loop FCNC electromagnetic penguin decay. Using much larger data samples, both Belle and BABAR have updated this analysis [91], and have added several new decay modes such as $B \to K_1\gamma$, $K_2^*(1430)\gamma$ *etc.* [92].

Compared to $b \to s\gamma$, the $b \to d\gamma$ transitions such as $B \to \rho\gamma$, are much suppressed because of the small CKM element V_{td}. Both BABAR and Belle have searched for these decays. Analyzing a sample of 3.86×10^8 $B\overline{B}$ pairs, Belle has obtained $\mathcal{B}(B \to (\rho,\omega)\gamma) = (1.32^{+0.34+0.10}_{-0.31-0.09}) \times 10^{-6}$ [93], where $B \to \rho\gamma$ and $\omega\gamma$ results are combined using isospin relations. On the other hand, using a sample of 2.11×10^8 $B\overline{B}$ pairs, BABAR obtained $\mathcal{B}(B \to (\rho,\omega)\gamma) < 1.2 \times 10^{-6}$ [94]. Using a theoretical calculation [95], a constraint on the magnitude of V_{td} is obtained from the Belle result: $|V_{td}/V_{ts}| = 0.199^{+0.026+0.018}_{-0.025-0.015}$ [93].

The observed branching fractions were used to constrain a large class of SM extensions [96]. 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. By combining the measurements of $B \to X_s\gamma$ from CLEO, Belle, and BABAR experiments [97], HFAG obtains the new average: $\mathcal{B}(B \to X_s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ [13]. Consistent results have been reported by ALEPH for inclusive b–hadrons produced at the Z. The measured branching fraction can be compared to recent theoretical calculations by Chetyrkin, Misiak, and Munz, and by Kagan and Neubert, which predict $\mathcal{B}(b \to s\gamma) = (3.29 \pm 0.33) \times 10^{-4}$ [98–100].

According to the SM, the CP asymmetry in $b \to s\gamma$ is smaller than 1 %, but some non-SM models allow significantly larger CP asymmetry ($\sim$ 10 %) without altering the inclusive branching fraction [101–103]. CLEO first searched for CP violation in this mode, and set a range on $A_{CP}(b \to s\gamma)$. Now, with improved measurements from Belle and BABAR, the range on $A_{CP}(b \to s\gamma)$ has become much more stringent. The average charge asymmetry calculated by HFAG is: $A_{CP} = -0.010 \pm 0.028$ [13].

In addition, all three experiments have measured the inclusive photon energy spectrum for $b \to s\gamma$, and by analyzing the shape of the spectrum they obtained the first and second moments for photon energies. The results on photon energy moments can be used to extract non-perturbative HQET parameters that are needed for precise determination of the CKM matrix element V_{ub}.

Additional information on FCNC processes can be obtained from $B \to X_s\ell^+\ell^-$ decays, which are mediated by electroweak penguin and W-box diagrams. Exclusive $B \to K\ell^+\ell^-$ decay was first observed by Belle [109]. Recently, both BABAR [110] and Belle [111] updated the measurements and the branching fractions are: $\mathcal{B}(B \to K\ell^+\ell^-) = (0.34 \pm 0.08) \times 10^{-6}$ (BABAR), and $(0.55 \pm 0.08) \times 10^{-6}$ (Belle). Similarly, the branching fraction for $B \to K^*(892)\ell^+\ell^-$ is also measured by both experiments: $\mathcal{B}(B \to K^*(892)\ell^+\ell^-) = (0.78^{+0.22}_{-0.21}) \times 10^{-6}$ (BABAR), and

$(1.65^{+0.25}_{-0.24}) \times 10^{-6}$ (Belle). There seem to be slight discrepancies between the two measurements; nevertheless, each one is consistent with the SM expectation.

Additional information on FCNC can be obtained from $B^0_{(s)} \rightarrow \mu^+\mu^-$ decays. These decays can only proceed at second order in weak interactions in the SM, but may have large contributions from Supersymmetric loops, proportional to $(\tan\beta)^6$. They have both been searched for, and CDF and D0 have both obtained results that start to exclude a portion of the region allowed by SUSY models. The current best limits are 1.5×10^{-7} and 0.39×10^{-7}, respectively, for B^0_s and B^0_d [20].

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. Evidences for direct CP violations have been observed. Many rare decays such as hadronic $b \rightarrow u$ transitions and $b \rightarrow s(d)$ gluonic penguin decays have been observed, and the emerging pattern is still full of surprises. The coming years look equally promising. With the two asymmetric B-factory experiments, Belle and BABAR, we now have a combined data sample of nearly 1 ab^{-1}, and the CKM picture of the CP violation is tested with better precision ever.

At Fermilab, CDF and D0 have accumulated approximately 1 fb^{-1}, which is the equivalent of 10^{11} B hadrons produced. Albeit with low reconstruction efficiency, this has allowed reconstruction of large samples of some modes, and has given a start to a program of studies on B_s and b-flavored baryons. Moreover, in about a year, the LHC will start operating and produce huge samples of B-hadrons.

These experiments promise a rich spectrum of rare and precise measurements that have the potential to fundamentally affect our understanding of the SM and CP-violating phenomena.

References

1. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

2. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **87**, 091801 (2001).
3. Belle Collab., K. Abe *et al.*, Phys. Rev. Lett. **87**, 091802 (2001).
4. Currently two different notations (ϕ_1, ϕ_2, ϕ_3) and (α, β, γ) are used in the literature for CKM unitarity angles. In this mini-review, we use the latter notation following the other mini-reviews in this *Review*. The two notations are related by $\phi_1 = \beta$, $\phi_2 = \alpha$ and $\phi_3 = \gamma$.
5. See the "Review on B-$\overline{B}$ Mixing" by O. Schneider in this *Review*.
6. See the "Determination of $|V_{cb}|$ and $|V_{ub}|$," by R. Kowalewski and T. Mannel in this *Review*.
7. See the "CP Violation in Meson Decays" by Y. Nir and D. Kirkby in this *Review*.
8. CLEO Collab., B. Barish *et al.*, Phys. Rev. Lett. **76**, 1570 (1996).
9. CLEO Collab., J.P. Alexander *et al.*, Phys. Rev. Lett. **86**, 2737 (2001).
10. BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D65**, 032001 (2001); BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D69**, 071101 (2004).
11. CLEO Collab., S.B. Athar *et al.*, Phys. Rev. **D66**, 052003 (2002).
12. Belle Collab., N.C. Hastings *et al.*, Phys. Rev. **D67**, 052004 (2003).
13. Heavy Flavor Averaging Group, E. Barberio *et al.*, "*Averages of b-hadron properties at the end of 2005*," `hep-ex/0603003` (2006).
14. Belle Collab., K. Abe *et al.*, Phys. Rev. Lett. **95**, 231802 (2005).
15. G. Punzi for the CDF Collab., *Proceedings of the 32nd International Conference on High-Energy Physics (ICHEP 04)*, `hep-ex/0504045`, Beijing, China (2004).
16. D. Tonelli for the CDF Collab., *Proceedings of International Europhysics Conference on High Energy Physics (HEP-EPS 2005)*, `hep-ex/0512024`, Lisbon, Portugal, 21-27 Jul 2005.
17. CDF Collab., D. Acosta *et al.*, `hep-ex/0508022`, submitted to Phys. Rev. Lett.
18. CDF Collab., F. Abe *et al.*, Phys. Rev. Lett. **81**, 2432 (1998); CDF Collab., F. Abe *et al.*, Phys. Rev. **D58**, 112004 (1998).

19. CDF Collab., D. Acosta *et al.*, Phys. Rev. Lett. **96**, 082002 (2006).
20. CDF Collab., D. Acosta *et al.*, Phys. Rev. Lett. **95**, 221805 (2005).
21. ALEPH Collab., D. Buskulic *et al.*, Phys. Lett. **B384**, 449 (1996).
22. DELPHI Collab., P. Abreu *et al.*, Z. Phys. **C68**, 541 (1995).
23. F. Ukegawa, "Spectroscopy and lifetime of bottom and charm hadrons," `hep-ex/0002031`, *Proceedings of 3rd International Conference on B Physics and CP Violation*, (BCONF99), Taipei, Taiwan, (1999).
24. D0 Collab., "Study of excited B-mesons," D0-note 4517 (http://www-d0.fnal.gov).
25. I.I. Bigi, UND-HEP-99-BIG07, `hep-ph/0001003`, *Proceedings of the 3rd International Conference on B Physics and CP Violation*, Taipei (1999).
26. D. Abbaneo *et al.*, "Combined results on b-hadron production rates and decay properties," CERN EP-2001/050 (2001).
27. I.I. Bigi *et al.*, in "B Decays," 2nd edition, S. Stone (ed.), World Scientific, Singapore, 1994.
28. C. Tarantino, Eur. Phys. J. **C33**, S895 (2004);
F. Gabbiani *et al.*, Phys. Rev. **D68**, 114006 (2003);
F. Gabbiani *et al.*, Phys. Rev. **D70**, 094031 (2004).
29. BABAR Collab., B. Aubert *et al.*, `hep-ex/0311037`, submitted to Phys. Rev. Lett.
30. A. Lenz, `hep-ph/0412007`; M. Beneke *et al.*, Phys. Lett. **B459**, 631 (1999).
31. See the "CKM Quark Mixing Matrix," by F.J. Gilman *et al.*, in this *Review*.
32. V. Ciulli, "Spectroscopy of excited b and c states", `hep-ex/9911044`, *Proceedings of the 8th International Conference on Heavy Flavours*, Southampton (1999).
33. N. Uraltsev, Phys. Lett. **B376**, 303 (1996).
34. M. Neubert and C.T. Sachrajda, Nucl. Phys. **B483**, 339 (1997).
35. J.L. Rosner, Phys. Lett. **B379**, 267 (1996).
36. M. Voloshin, Phys. Reports **320**, 275 (1999).
37. B. Guberina *et al.*, Phys. Lett. **B469**, 253 (1999).
38. P. Colangelo and F. De Fazio, Phys. Lett. **B387**, 371 (1996);

P. Colangelo, *Proceedings of the 28th International Conference on High Energy Physics*, Warsaw (1996).

39. G. Altarelli *et al.*, Phys. Lett. **B382**, 409 (1996).
40. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002).
41. Belle Collab., K. Abe *et al.*, Belle-CONF-0353 (2003).
42. Y. Grossman and M.P. Worah, Phys. Lett. **B395**, 241 (1997).
43. BABAR Collab., Preliminary result presented at Lepton-Photon 2003 (2003).
44. Belle Collab., K. Abe *et al.*, Phys. Rev. **D68**, 012001 (2003).
45. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **94**, 181802 (2005).
46. Belle Collab., Y. Chao *et al.*, Phys. Rev. Lett. **94**, 181803 (2005).
47. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **94**, 131801 (2005).
48. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **95**, 041805 (2005).
49. Belle Collab., A. Somov *et al.*, `hep-ex/0601024`, to appear in Phys. Rev. Lett.
50. BABAR Collab., B. Aubert *et al.*, `hep-ex/0408099`.
51. Belle Collab., C.C. Wang *et al.*, Phys. Rev. Lett. **94**, 121801 (2005).
52. See, for example, "The BABAR Physics Book," SLAC-R-504, P.F. Harrison and H.R. Quinn, Eds., and references therein.
53. M. Gronau and D. London, Phys. Lett. **B253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. **B265**, 172 (1991).
54. D. Atwood *et al.*, Phys. Rev. Lett. **78**, 3257 (1997); Phys. Rev. **D63**, 036005 (2001).
55. A. Giri *et al.*, Phys. Rev. **D68**, 054018 (2003).
56. BABAR Collab., B. Aubert *et al.*, `hep-ex/0512067`; Phys. Rev. **D71**, 031102 (2005); Phys. Rev. **D72**, 071103R (2005);
    Phys. Rev. **D72**, 032004 (2005); `hep-ex/0512067`.
57. Belle Collab., K. Abe *et al.*, `hep-ex/0601032`; `hep-ex/0307074`; `hep-ex/0508048`.
58. Belle Collab., K. Abe *et al.*, `hep-ex/0411049`; `hep-ex/0504013`.

59. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **95**, 121802 (2005); `hep-ex/0507101`.
60. CKMfitter Group, J. Charles *et al.*, Eur. Phys. J. **C41**, 1 (2005); UTfit Collab., M. Bona *et al.*, JHEP **0507**, 028 (2005).
61. M. Neubert, "Aspects of QCD Factorization," `hep-ph/0110093`, *Proceedings of HF9*, Pasadena (2001) and references therein.
62. Z. Ligeti *et al.*, Phys. Lett. **B507**, 142 (2001).
63. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **90**, 242001 (2003).
64. CLEO Collab., D. Besson *et al.*, Phys. Rev. **D68**, 032002 (2003).
65. Belle Collab., P. Krokovny *et al.*, Phys. Rev. Lett. **91**, 262002 (2003).
66. Belle Collab., S.-K. Choi *et al.*, Phys. Rev. Lett. **91**, 262001 (2003).
67. CDF II Collab., D. Acosta *et al.*, Phys. Rev. Lett. **93**, 072001 (2004); BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D71**, 071103 (2005).
68. Belle Collab., K. Abe *et al.*, Phys. Rev. Lett. **93**, 051803 (2004).
69. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **93**, 041801 (2004).
70. BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D71**, 031501 (2005).
71. Belle Collab., S.-K. Choi *et al.*, Phys. Rev. Lett. **94**, 182002 (2005).
72. BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D73**, 011101 (2006).
73. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **95**, 142001 (2005).
74. CDF Collab., D. Acosta *et al.*, Phys. Rev. Lett. **95**, 031801 (2005).
75. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **95**, 221801 (2005).
76. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **93**, 131801 (2004); Belle Collab., Y. Chao *et al.*, Phys. Rev. Lett. **93**, 191802 (2004).
77. Belle Collab., K. Abe *et al.*, `hep-ex/0507045`.
78. M. Gronau, Phys. Lett. **B492**, 297 (2000); M. Gronau and J. L. Rosner, Phys. Lett. **B482**, 71 (2000).

79. H. Lipkin, Phys. Lett. **B621**, 126 (2005).
80. Belle Collab., K. Abe *et al.*, `hep-ex/0509001`.
81. BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D72**, 072003 (2005).
82. M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990).
83. R. Fleischer, Phys. Lett. B**459**, 306 (1999); D. London and J. Matias, Phys. Rev. **D70**, 031502 (2004).
84. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **94**, 131801 (2005).
85. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **91**, 171802 (2003); Belle Collab., J. Zhang *et al.*, Phys. Rev. Lett. **91**, 221801 (2003).
86. See the “Polarization in B Decays,” by A. Gritsan and J. Smith in this *Review*.
87. Belle Collab., P. Krokovny *et al.*, Phys. Rev. Lett. **89**, 231804 (2002).
88. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **90**, 181803 (2003).
89. BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D73**, 011103 (2006).
90. CLEO Collab., R. Ammar *et al.*, Phys. Rev. Lett. **71**, 674 (1993).
91. Belle Collab., M. Nakao *et al.*, Phys. Rev. **D69**, 112001 (2004); BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D70**, 112006 (2004).
92. Belle Collab., H. Yang *et al.*, Phys. Rev. Lett. **94**, 111802 (2005); BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D70**, 091105R (2004); Belle Collab., S. Nishida *et al.*, Phys. Lett. **B610**, 23 (2005).
93. Belle Collab., D. Mohapatra *et al.*, `hep-ex/0506079`, submitted to Phys. Rev. Lett.
94. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **94**, 011801 (2005).
95. A. Ali *et al.*, Phys. Lett. **B595**, 323 (2004).
96. J.L. Hewett, Phys. Rev. Lett. **70**, 1045 (1993).
97. CLEO Collab., S. Chen *et al.*, Phys. Rev. Lett. **87**, 251807 (2001);
Belle Collab., K. Abe *et al.*, Phys. Lett. **B511**, 151 (2001);
Belle Collab., P. Koppenburg *et al.*, Phys. Rev. Lett. **93**, 061803 (2004);
BABAR Collab., B. Aubert *et al.*, Phys. Rev. **D72**,

052004 (2005);
BABAR Collab., B. Aubert *et al.*, `hep-ex/0507001`.

98. K. Chetyrkin *et al.*, Phys. Lett. **B400**, 206 (1997); Erratum-ibid, Phys. Lett. **B425**, 414 (1998).
99. A.J. Buras *et al.*, Phys. Lett. **B414**, 157 (1997); Erratum-ibid, Phys. Lett. **B434**, 459 (1998).
100. A.L. Kagan and Matthias Neubert, Eur. Phys. J. **C7**, 5 (1999).
101. K. Kiers *et al.*, Phys. Rev. **D62**, 116004 (2000).
102. A.L. Kagan and M. Neubert, Phys. Rev. **D58**, 094012 (1998).
103. S. Baek and P. Ko, Phys. Rev. Lett. **83**, 488 (1998).
104. CLEO Collab., T.E. Coan *et al.*, Phys. Rev. Lett. **86**, 5661 (2001).
105. Belle Collab., K. Abe *et al.*, Belle-CONF-0348 (2003).
106. CLEO Collab., T.E. Coan *et al.*, Phys. Rev. Lett. **84**, 5283 (2000).
107. BABAR Collab., B. Aubert *et al.*, Phys. Rev. Lett. **88**, 101805 (2002).
108. CLEO Collab., S. Chen *et al.*, Phys. Rev. Lett. **87**, 251807 (2001).
109. Belle Collab., K. Abe *et al.*, Phys. Rev. Lett. **88**, 021801 (2001).
110. BABAR Collab., B. Aubert *et al.*, `hep-ex/0507005`.
111. Belle Collab., K. Abe *et al.*, `hep-ex/0410006`.