PRODUCTION AND DECAY OF b-FLAVORED HADRONS

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The b quark belongs to the third generation of quarks and is the 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), and confirmed four years later by the first observation of a $b\overline{b}$ meson [2]. In the KM model, CP violation is explained within the Standard Model (SM) by an irreducible phase of the 3×3 unitary 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 SM, including the fermion masses, and the elements of the CKM matrix.

Since the b quark is the lighter element of the third–generation quark doublet, the decays of b-flavored hadrons occur via generation-changing processes through this matrix. Because of this and the fact that the CKM matrix is 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 large CP asymmetries, can be observed in the weak decays of b-flavored hadrons. The CKM matrix is parameterized by three real parameters and one complex phase. This complex phase can become a source of CP violation in B meson decays. A crucial milestone in 2001 was the first observation of CP violation in the B meson system by the BaBar [3] and Belle [4] collaborations. They measured a large value for the parameter $\sin 2\beta$ $(= \sin 2\phi_1)$ [5], almost four decades after the discovery of a small CP asymmetry in neutral kaons. A more detailed discussion of the CKM matrix and CP violation can be found elsewhere in this *Review* [6,7].

Recent developments in the physics of b-hadrons include the observation of direct CP violation, results for rare higher-order-weak decays, investigations of heavier b-hadrons (B^0_s, B_c, baryons, excited states), measurement of the B^0_s-mixing frequency, increasingly accurate determinations of the CKM

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matrix elements V_{cb} and V_{ub}, and of the angles α and γ of the unitarity triangle.

The structure of this mini-review is organized as follows. After a brief description of theory and terminology, we discuss b-quark production and current results on spectroscopy and lifetimes of b-flavored hadrons. We then discuss some basic properties of B-meson decays, followed by summaries of hadronic, rare, and electroweak penguin decays of B-mesons. There are separate mini-reviews for $B\overline{B}$ mixing [8] and the extraction of the CKM matrix elements V_{cb} and V_{ub} from B-meson decays [9] in this *Review.*

Theory and terminology: The ground states of b-flavored hadrons decay via weak interactions. In most hadrons, the b-quark is accompanied by light-partner quarks (d, u, or s), and the decay modes are well described by the decay of the b quark (spectator model) [10]. The dominant decay mode of a b quark is $b \to cW^{*-}$ (referred to as a “tree” or “spectator” decay), where the virtual W^* materializes either into a pair of leptons, $\ell\bar{\nu}$ (“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^* to form one of the final state hadrons are suppressed by a factor $\simeq 1/9$, because the colors of the two quarks from different sources must match (“color–suppression”).

Many aspects of B decays can be understood with the use of Heavy Quark Effective Theory (HQET) [11]. This has been particularly successful for semileptonic decays. For further discussion of HQET, see for instance Ref. 9. For hadronic decays, one typically uses effective Hamiltonian calculations that rely on a perturbative expansion with Wilson coefficients. In addition, some form of the factorization hypothesis is commonly used, where, in analogy with semileptonic decays, two-body hadronic decays of B mesons are expressed as the product of two independent hadronic currents, one describing the formation of a charm meson (in case of the dominant $b \to cW^{*-}$ decays), 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 (produced as a color singlet) travels fast enough to leave the interaction region without influencing the charm meson. This is known to work well for the dominant spectator decays [12]. There are several common implementations of these ideas for hadronic B decays, the most common of which are QCD factorization (QCDF) [13], perturbative QCD (pQCD) [14], and soft collinear effective theory (SCET) [15].

The transition $b \to u$ is suppressed by $|V_{ub}/V_{cb}|^2 \sim (0.1)^2$ relative to $b \to c$ transitions, and gives way to rarer decay modes, *e.g.*, loop-induced $b \to s$ decays. The transition $b \to s$ is a flavor-changing neutral-current (FCNC) process, and although not allowed in the SM as a tree-process, can occur via more complex diagrams (denoted "penguin" decays). The rates for such processes are comparable or larger than CKM-suppressed $b \to u$ processes. Penguin processes involving $b \to d$ transitions are also possible, and have recently been observed [16,17]. Other decay processes discussed in this *Review* include W–exchange (a W is exchanged between initial–state quarks), penguin annihilation (the gluon from a penguin loop attaches to the spectator quark, similar to an exchange diagram), and pure–annihilation (the initial quarks annihilate to a virtual W, which then decays).

Production and spectroscopy: The bound states of 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^0, and B_c^+ mesons, respectively. The B_c^+ is the heaviest of the ground–state b-flavored mesons, and the most difficult to produce; it was observed for the first time in the semileptonic mode by CDF in 1998 [18], but its mass was accurately determined only in 2006 from the fully reconstructed mode $B_c^+ \to J/\psi\pi^+$ [19].

The first excited meson 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^{**}. Of the possible bound $\overline{b}b$ states, the Υ series (S-wave) and the χ_b (P-wave) are well studied; see Ref. 20 for classification and naming of these and other $\overline{b}b$ states.

Experimental studies of b decays have been performed in e^+e^- collisions at the $\Upsilon(4S)$ resonance (ARGUS, CLEO, Belle, and BaBar), as well as at higher energies at the Z resonance

(SLC and LEP) and in $p\bar{p}$ collisions (Tevatron). The $e^+e^- \rightarrow b\overline{b}$ 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 produce b-flavored hadrons of all species with a very large cross-section ($\sigma(p\overline{p} \rightarrow bX, |\eta| < 1) \sim 30$ μb at the Tevatron, which is expected to be ten times larger at the LHC pp collider with $\sqrt{s} = 14$ TeV). The total b-production cross section in hadronic collision is an interesting test of our understanding of QCD processes. For many years, experimental measurements have been several times higher than predictions. With improved measurements [21], more accurate input parameters, and more advanced calculations [22], the discrepancy between theory and data is now much reduced, although the presence of inconsistencies among existing measurements makes further data desirable.

As of this writing, BaBar and Belle have accumulated approximately 500 fb^{-1} and 700 fb^{-1}, respectively, and CDF and D0 have each accumulated about 2.5 fb^{-1}. Although these numbers imply that the majority of b-quarks are produced in hadron collisions, the large backgrounds cause the hadron collider experiments to have lower efficiency. Only the few decay modes for which triggering and reconstruction are easiest have been studied so far in hadron collisions. These have included final states with leptons, and the exclusive modes into all charged particles. In contrast, detectors operating at the $\Upsilon(4S)$ ("B-Factories") have a high efficiency for most decays, and have provided large samples of a rich variety of decays of B^0 and B^+ mesons.

In hadron collisions, most production happens as $b\overline{b}$ pairs, either via s-channel production or gluon–splitting, with a smaller fraction of single b-quarks produced by flavor excitation. After production, each quark of a $b\overline{b}$ pair hadronizes separately and incoherently from the other, but it is still possible, although difficult, to obtain a statistical indication of the charge of a produced $b/\overline{b}$ quark ("flavor tag" or "charge tag") from the accompanying particles produced in the hadronization process, or from the decay products of the other quark. The momentum spectrum of produced b-quarks typically peaks near the b-quark mass, and extends to much higher momenta, dropping by about a decade for every ten GeV. This implies typical decay lengths of a *mm*, that are important to resolve the fast oscillations of B_s^0 mesons.

In e^+e^- colliders, since the B mesons are very slow in the $\Upsilon(4S)$ rest frame, asymmetric beam energies are used to boost the decay products to improve the precision of time-dependent measurements that are crucial for the study of CP violation. At KEKB, 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, $\beta\gamma = 0.55$. The two B mesons produced in $\Upsilon(4S)$ decay are in a coherent quantum state, which makes it easier than in hadron collision to infer the charge state of one B meson from observation of the other; however, the coherence also requires to determine the decay time of both mesons, rather than just one, in order to perform time–dependent CP–violation measurements.

For the measurement of branching fractions, the initial composition of the data sample must be known precisely. The $\Upsilon(4S)$ resonance decays predominantly to $B^0\overline{B}^0$ and B^+B^-; the current experimental upper limit for non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is less than 4% at the 95% confidence level (CL) [23]. The only known modes of this category are decays to lower Υ states and a pion pair, recently observed with branching fractions of order 10^{-4} [24]. The ratio f_+/f_0 of the fractions of charged to neutral B productions from $\Upsilon(4S)$ decays has been measured by CLEO, BaBar, and Belle in various ways, typically based on pairs of isospin-related decays of B^+ and B^0, such that it can be assumed that $\Gamma(B^+ \to x^+) = \Gamma(B^0 \to x^0)$. In this way, the ratio of the number of events observed in these modes is proportional to $(f_+\tau_+)/(f_0\tau_0)$ [25–28]. BaBar has also performed an independent measurement of f_0 with a different method that does not require isospin symmetry or the value of the lifetime ratio, based on the number of events with one or two reconstructed $B^0 \to D^{*-}\ell^+\nu$ decays [29]. The combined result, from the current average of τ_+/τ_0, is $f_+/f_0 = 1.065 \pm 0.026$ [30]. This number is currently a bit less consistent with equal production of B^+B^- and $B^0\overline{B}^0$ pairs than it used to be in the past (deviates from unity by 2.5σ), but we still assume $f_+/f_0 = 1$ in this mini-review except where explicitly stated otherwise. This assumption is also supported by the near equality of the B^+ and B^0 masses: our fit of CLEO, ARGUS, and CDF measurements yields $m(B^0) = 5279.50 \pm 0.33$ MeV/c^2, $m(B^+) = 5279.13 \pm 0.31$ MeV/c^2, and $m(B^0) - m(B^+) = 0.37 \pm 0.24$ MeV/c^2.

CLEO and Belle have also collected some data at the $\Upsilon(5S)$ resonance [31,32]. They measured the fraction of events with a pair of B_s^0 mesons over the total number of events with a pair of b-flavored hadrons. Their combined result is $f_s[\Upsilon(5S)] = 0.199 \pm 0.029$, thus establishing an alternative way of producing samples of B_s^0 mesons, dominated by production of $B_s^{*0}\bar{B}_s^{*0}$ events. However, the small boost of B_s^0 mesons produced in this way prevents resolution of their fast oscillations for time-dependent measurements; these are only accessible in hadron collisions or at the Z peak.

In high-energy collisions, the produced b or $\bar{b}$ quarks can hadronize with different probabilities into the full spectrum of b-hadrons, either in their ground or excited states. Table 1 shows the measured fractions f_d, f_u, f_s, and f_{baryon} of B^0, B^+, B_s^0, and b baryons, respectively, in an unbiased sample of weakly decaying b hadrons produced at the Z resonance and in $p\overline{p}$ collisions [30]. The results were obtained from a fit where the sum of the fractions were constrained to equal 1.0, neglecting production of B_c mesons. The observed yields of B_c mesons at the Tevatron [18], provide an estimate $f_c = 0.2\%$, in agreement with expectations [33], which is below the current experimental uncertainties in the other fractions.

The combined values assume identical hadronization in $p\overline{p}$ collisions and in Z decay. These could in principle differ, because of the different momentum distributions of the b-quark in these processes; the sample used in the $p\overline{p}$ measurements has momenta close to the b mass, rather than $m_Z/2$. A test of the agreement between production fractions may be given by comparison of values of the average time-integrated mixing probability parameter $\bar{\chi} = f_d\chi_d + f_s\chi_s$ [8], which is an important input in the determination of the world-averages of production fractions. The current measurements of $\overline{\chi}$ from LEP and Tevatron differ by 1.8σ [30]. This slight discrepancy causes a larger uncertainty in the combined fractions in Table 1. With the availability of increasing large samples of b-flavored mesons and baryons at $p\overline{p}$ colliders, the limited knowledge of these fractions has become an important limiting factor in the determination of their branching fractions.

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

b hadron	Fraction at Z [%]	Combined with $\overline{p}p$ [%]
B^+, B^0	40.2 ± 0.9	39.9 ± 1.1
B^0_s	10.5 ± 0.9	11.1 ± 1.2
b baryons	9.1 ± 1.5	9.2 ± 1.9

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^{**} (L=1) production has been presented by the LEP and CDF experiments [34], as a broad resonance in the mass of an inclusively reconstructed bottom hadron candidate combined with a charged pion from the primary vertex. Results with exclusive modes have been obtained at the Tevatron, allowing separation of the narrow states, B_1 and B_2^*. The D0 collaboration measures $M(B_1) = 5720.6 \pm 2.4 \pm 1.4$ MeV/c^2 and $M(B_2^*) - m(B_1) = 26.2 \pm 3.1 \pm 0.9$ MeV/c^2 [35].

The narrow B_s^{**} states, first sighted by OPAL as a single broad enhancement in the B^+K mass spectrum [36], have now been clearly observed and separately measured at the Tevatron [37]: $M(B_{s1}) = 5829.4 \pm 0.7$ MeV/c^2 (CDF) and $M(B_{s2}^*) = 5839.7 \pm 0.7$ MeV/c^2 (CDF), $M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7$ MeV/c^2 (D0).

Baryon states containing a b quark are labeled according to the same scheme used for non-b baryons, with the addition of a b subscript [20]. For many years, the only well-established b baryon was the Λ_b^0 (quark composition udb); only indirect evidence for Ξ_b (dsb) production had been obtained at LEP [38]. This situation is now rapidly changing due to the large samples being accumulated at the Tevatron. Clear signals of four baryon states, Σ_b^+, Σ_b^{*+} (uub), Σ_b^-, Σ_b^{*-} (ddb) have been obtained by CDF in $\Lambda_b^0\pi^\pm$ final state [39]. The strange bottom baryon $\Xi_b^\pm$ has been observed in the exclusive mode $\Xi_b^\pm \to J/\psi\Xi^\pm$ by D0 [40], and CDF [41]. The masses of all these new baryons have been measured to a precision of a few MeV/c^2, and found to be in agreement with predictions from HQET. The relative production of Ξ_b and Λ_b baryons has been found to be consistent with the B_s to B_d production ratio [40].

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. Non–spectator 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 variations in the b system are expected to be significantly smaller; on the order of 10% or less [42]. 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 a 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 precision of silicon vertex detectors, and the increasing availability of fully–reconstructed samples, yielded measurements with much-reduced statistical and systematic uncertainties, at the 1% level. The averaging of precision results from different experiments is a complex task that requires careful treatment of correlated systematic uncertainties; the world averages given in this mini-review (Table 2) have been determined by the Heavy Flavor Averaging Group (HFAG) [30].

Table 2: Summary of inclusive and exclusive world-average b-hadron lifetime measurements. For the two B_s^0 averages, see text below.

Particle	Lifetime [ps]
B^+	1.638 ± 0.011
B^0	1.530 ± 0.009
B_s^0	1.417 ± 0.042 (flavor-specific)
B_s^0	$1.437^{+0.031}_{-0.030}$ $(1/\Gamma_s)$
B_c^+	0.463 ± 0.071
Λ_b	$1.383^{+0.049}_{-0.048}$
Ξ_b mixture	$1.42^{+0.28}_{-0.24}$
b-baryon mixture	$1.319^{+0.39}_{-0.38}$
b-hadron mixture	1.568 ± 0.009

The short B_c^+ lifetime is in good agreement with predictions [43]. For precision comparisons with theory, lifetime ratios are more sensitive. Experimentally we find:

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.071 \pm 0.009\,, \quad \frac{\tau_{B_s^0}}{\tau_{B^0}} = 0.939 \pm 0.021\,,$$

$$\frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.904 \pm 0.032\,,$$

while theory makes the following predictions [42,44]

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.06 \pm 0.02\ , \quad \frac{\tau_{B_s^0}}{\tau_{B^0}} = 1.00 \pm 0.01\ , \quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.88 \pm 0.05.$$

The ratio of B^+ to B^0 is measured to better than 1%, and is significantly different from one, in agreement with predictions [42]. Conversely, the ratio of B_s^0 to B^0 lifetimes is expected to be very close to one, but exhibits a 2.5σ deviation. The Λ_b lifetime has a history of discrepancies. Predictions used to be higher than data, before the introduction of higher-order effects lowered them. The latest measurements, from CDF on the exclusive $J/\psi\Lambda$ mode [45], and from D0 [46] on both semileptonic and $J/\psi\Lambda$ mode, disagree at the 3σ level. Further measurements will help clarify the situation in the future.

Neutral B mesons are two-component systems similar to neutral kaons, with a light (L) and a heavy (H) mass eigenstate, and independent decay widths Γ_L and Γ_H. The SM predicts a non-zero width difference $\Delta\Gamma = \Gamma_L - \Gamma_H > 0$ for both B_s and B_d. For B_d, $\Delta\Gamma_d/\Gamma_d$ is expected to be ∼0.2%. Analysis of BaBar and DELPHI data on CP-specific modes of the B^0 yield a combined result: $\Delta\Gamma_d/\Gamma_d = 0.009 \pm 0.037$ [30]. The issue is much more interesting for the B_s, since the SM expectation for $\Delta\Gamma_s/\Gamma_s$ is of order 10%. This potentially non-negligible difference requires care when defining the B_s^0 lifetime.

As indicated in Table 2, two different lifetimes are defined for the B_s^0 meson: one is defined as $1/\Gamma_s$, where Γ_s is the average width of the two mass eigenstates $(\Gamma_L + \Gamma_H)/2$; the other is obtained from "flavor-specific" decays (*e.g.*, semileptonic) and depends both on Γ_s and $\Delta\Gamma_s$. Experimentally, the quantity $\Delta\Gamma_s$ can be accessed by measuring lifetimes in decays into CP eigenstates, which are expected to be close approximations to the mass eigenstates. This has been done with the $J/\psi\phi$ mode, where the two CP eigenstates are distinguished by angular distributions, and in $B_s^0 \to K^+K^-$ which is dominated by a single CP-state. The current experimental information is dominated by CDF and D0 measurements on the $J/\psi\phi$ mode. By appropriately combining all published measurements of $J/\psi\phi$ lifetimes and flavor-specific lifetimes, the HFAG group obtains a world-average $\Delta\Gamma_s/\Gamma_s = 0.121^{+0.083}_{-0.090}$ [30]; the quoted uncertainties are, however, non-Gaussian, and a better representation of the current uncertainty is given by the 95% CL interval: $-0.06 < \Delta\Gamma_s/\Gamma_s < 0.28$ [30], which is still compatible with zero. The latest predictions yield $\Delta\Gamma_s/\Gamma_s = 0.147 \pm 0.060$ [47], in agreement with the experiment within the large uncertainties on both. The experimental precision can still improve in the near future with the growth of Tevatron samples; a very recent update by CDF, not yet included in the above average yields already a significant improvement: $\Delta\Gamma_s = 0.076^{+0.059}_{-0.063} \pm 0.006$ ps^{-1} [48]. D0 combined the contour in the $(\phi_s, \Delta\Gamma)$ plane (ϕ_s is the B_s^0 mixing phase) with a constraint obtained from the charge asymmetry in B_s^0 oscillations to obtain the result $\Delta\Gamma_s = 0.13 \pm 0.09$ ps^{-1} [49]. Further improvements may come from $B_s^0 \to K^+K^-$, and alternative (model–dependent) determinations via the $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ branching fraction [50].

From the theoretical point of view, the best quantity to use is $\Delta\Gamma_s/\Delta M_s$, which is much less affected by hadronic uncertainties: $\Delta\Gamma_s/\Delta M_s = (49.7 \pm 9.4) \times 10^{-4}$ [47]. Exploiting the very accurate measurement of ΔM_s now available [51], this can be turned into a SM prediction with just 20% uncertainty: $\Delta\Gamma_s/\Gamma_s = 0.127 \pm 0.024$. This is likely to be of importance in future comparisons to improved measurements.

B meson decay properties: Semileptonic B decays $B \to X_c\ell\nu$ and $B \to X_u\ell\nu$ provide an excellent way to measure the magnitude of the 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 and inclusive decays can be used, and the nature of uncertainties are quite complementary. For exclusive decay analysis, knowledge of the form factors for the exclusive hadronic system $X_{c(u)}$ is required. For inclusive analysis, it is usually necessary 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 B semileptonic decays and the extraction of $|V_{cb}|$ and $|V_{ub}|$ is given elsewhere in this *Review* [9].

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. Pure–penguin decays were first established by the observation of $B \to K^*\gamma$ [52]. Some observed decay modes such as $B^0 \to D_s^- K^+$, may be interpreted as evidence of a W-exchange process [53]. The recent evidence for the decay $B^+ \to \tau^+\nu$ from Belle [54] and BaBar [55] is the first sign of a pure annihilation decay.

There is growing evidence that penguin annihilation processes may be important in decays with two vector mesons in the final state [56].

Hadronic decays:

Most of the hadronic B decays involve $b \to c$ transition at the quark level, resulting in a charmed hadron or charmonium in the final state. Other types of hadronic decays are very rare and will be discussed separately in the next section. The experimental results on hadronic B decays have steadily improved over the past few years, and the measurements have reached sufficient precision to challenge our understanding of the dynamics of these decays. With the 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 for suppressing 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.

The kinematically clean environment of B meson decays provides an excellent opportunity 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 $D^*_{sJ}(2317)$ [57], and CLEO observed a similar state $D_{sJ}(2460)$ [58]. However, the properties of these new states were not well known until Belle observed $B \to DD^*_{sJ}(2317)$ and $B \to DD_{sJ}(2460)$, which helped identify some quantum numbers of $D_{sJ}(2460)$ [59]. Further studies of $D^{(*)}_{sJ}$ meson production 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 a sample of 449 million $B\overline{B}$ pairs, Belle has observed a new D_{sJ} meson produced in $B^+ \to \bar{D}^0 D_{sJ} \to \bar{D}^0 D^0 K^+$ [60]. The mass and width of this state are measured to be $2708 \pm 9^{+11}_{-10}$ MeV/c^2 and $108 \pm 23^{+36}_{-31}$ MeV, respectively. An analysis of the helicity angle distribution determines its spin-parity to be 1^-.

A variety of exotic particles have been discovered in B decays. Belle found the $X(3872)$ state [61], confirmed by CDF [62] and BaBar [64]. Belle has observed a near-threshold enhancement in the $\omega J/\psi$ invariant mass for $B \to K\omega J/\psi$ decays [65]. BaBar has studied $B \to J/\psi\pi^+\pi^- K$, finding an excess of $J/\psi\pi^+\pi^-$ events with a mass just above 4.2 GeV/c^2; this is consistent with the $Y(4260)$ that was observed by BaBar in ISR (Initial State Radiation) events [67]. A Belle study of $B \to K\pi^\pm\psi'$ [68] finds a state called $Z^\pm(4430)$ that decays to $\pi^\pm\psi'$. Since it is charged, it cannot be a charmonium state. More details about these exotic states are described in a separate mini-review [69] in this *Review*.

There have been hundreds of publications on hadronic B decays to open-charm and charmonium final states mostly from the B-factory experiments. These results are nicely summarized in a recent report by HFAG [30].

Rare B decays: All B-meson decays that do not occur through the $b \to c$ 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 $b \to s(d)$ 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. Since the final state particles in these decays tend to have larger momenta than average B decay products, the event environment is cleaner than for $b \to c$ decays. Branching fractions are typically around 10^{-5}. Over the past decade, 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 the impact parameter of the charged tracks. This also allowed observation of charmless decays of the B_s for the first time, in the final states $\phi\phi$ [70] and K^+K^- [71].

Because of relatively high-momenta for final state particles, the dominant source of background in e^+e^- collisions is $q\bar{q}$ continuum events; sophisticated background suppression techniques exploiting 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 kinematic and isolation requirements. The results are in general consistent among the four experiments.

BaBar [72] and Belle [73] have recently observed the decays $B^+ \to \overline{K}^0 K^+$ and $B^0 \to K^0 \overline{K}^0$. The world-average branching fractions are $\mathcal{B}(B^0 \to K^0 \overline{K}^0) = (0.96^{+0.20}_{-0.18}) \times 10^{-6}$ and $\mathcal{B}(B^+ \to \overline{K}^0 K^+) = (1.36 \pm 0.27) \times 10^{-6}$. These are the first observations of hadronic $b \to d$ transitions, with significance $> 5\sigma$ for all four measurements. CP asymmetries have even been measured for these modes, though with large errors.

Most rare decay modes including $B^0 \to K^+\pi^-$ have contributions from both $b \to u$ tree and $b \to sg$ penguin processes. If the size of the two contributions are comparable, the interference between them may result in direct CP violation, seen experimentally as a charge asymmetry in the decay rate measurement. BaBar [74], Belle [75], and CDF [76] have measured the direct CP violating asymmetry in $B^0 \to K^+\pi^-$ decays. The BaBar measurement, $A_{CP}(K^+\pi^-) = -0.107 \pm 0.018^{+0.007}_{-0.004}$, constitutes observation of direct CP violation with a significance of 5.5σ. The world average for this quantity is now rather precise, -0.101 ± 0.015. There are sum rules that relate the decay rates and decay-rate asymmetries between the four $K\pi$ charge states. The experimental measurements of the other three modes are not yet precise enough to test these sum rules.

There is now evidence for direct CP violation in three other decays: $B^+ \to \rho^0 K^+$ [77], $B^+ \to \eta K^+$ [78], and $B^0 \to \eta K^{*0}$ [79]. The significance is typically 3–4σ. In at least the first two cases, a large direct CP violation might be expected since the penguin amplitude is suppressed so the tree and penguin amplitudes may have comparable magnitudes.

The decay $B^0 \to \pi^+\pi^-$ can be used to extract the CKM angle α. This is complicated by the presence of significant contributions from penguin diagrams. An isospin analysis [80] can be used to untangle the penguin complications. The decay $B^0 \to \pi^0\pi^0$, which is now measured by both BaBar and Belle, is crucial in this analysis. Unfortunately the amount of penguin pollution in the $B \to \pi\pi$ system is rather large. In the past two years, measurements in the $B^0 \to \rho\rho$ system have produced more precise values of α, since penguin amplitudes are generally smaller for decays with vector mesons. An important ingredient in the analysis is the $B^0 \to \rho^0\rho^0$ branching fraction. Evidence for this mode has now been found by BaBar [81] with a branching fraction of $(1.07 \pm 0.33 \pm 0.19) \times 10^{-6}$. This is only 4% of the $\rho^+\rho^-$ branching fraction, much smaller than the corresponding ratio in the $\pi\pi$ system.

The decay $B \to a_1\pi$ has now been seen by BaBar [82]. This decay can be used to constrain the CKM angle α [83] though there are not yet suitable constraints on the penguin pollution in this system.

Since $B \to \rho\rho$ has 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 measurement of f_L is needed to extract the CKM angle α. Both BaBar and Belle have measured the f_L for the decays $\rho^+\rho^-$ and $\rho^+\rho^0$ and in both cases the measurements show $f_L > 0.9$, making a complete angular analysis unnecessary.

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. Decays that are penguin-dominated (such as $B \to \phi K^*$) surprisingly have values of f_L near 0.5. The reasons for this are not understood. A detailed description of the angular analysis of B decays to two vector mesons can be found in a separate mini-review [84] in this *Review* .

There has been substantial progress in measurements of many other rare-B decays. The decay $B \to \eta' K$ stood out as the largest rare-B decay for many years. The reasons for the large rate are now largely understood [13,85]. However, there are now measurements of several 3-body or quasi-3-body modes with similarly large branching fractions. States seen so far include $K\pi\pi$ (three charge states) [86], KKK (four charge states) [87], and $K^*\pi\pi$ (two charged states) [88]. Several of these analyses now include quite sophisticated Dalitz plot analyses with many intermediate resonances. There has also been a recent observation of the decay $B^+ \to K^+K^-\pi^+$ by BaBar [89], noteworthy because an even number of kaons is typically indicative of suppressed $b \to d$ transitions as discussed above.

Belle [54] and BaBar [55] have found evidence for $B^+ \to \tau^+\nu$ with a combined branching fraction of $(140 \pm 40) \times 10^{-6}$ in excellent agreement with the value expected in the Standard Model. This is the first evidence for a pure annihilation decay.

The recently observed $B_s \to K^+K^-$ mode [71] is related to $B^0 \to \pi^+\pi^-$ by U-spin symmetry, and is similarly determined by a superposition of tree and penguin diagrams. Combining the observables from these two modes is another way of eliminating hadronic uncertainties and extracting relevant CKM information [90].

Electroweak penguin decays:

More than a decade has passed since the CLEO experiment first observed an exclusive radiative $b \to s\gamma$ transition, $B \to K^*(892)\gamma$ [52], 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 suppressed by the small CKM element V_{td}. Both BaBar and Belle have observed these decays [16,17]. The world average $\mathcal{B}(B \to (\rho,\omega)\gamma) = (1.28 \pm 0.21) \times 10^{-6}$. This can be used to calculate $|V_{td}/V_{ts}|$ [93]; both BaBar and Belle find a value of 0.20 ± 0.03.

The observed radiative penguin branching fractions can constrain a large class of SM extensions [94]. 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 [95], HFAG obtains the new average: $\mathcal{B}(B \to X_s\gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$ [30]. Consistent results have been reported by ALEPH for inclusive b–hadrons produced at the Z. The measured branching fraction can be compared to theoretical calculations [96–98]. They predict $\mathcal{B}(b \to s\gamma) = (3.29 \pm 0.33) \times 10^{-4}$.

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 [99–101]. The current world average is $A_{CP} = 0.004 \pm 0.037$, again dominated by BaBar and Belle [102].

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 obtain the first and second moments for photon energies. These results 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. Belle [103] and BaBar [104] have measured the branching fractions for $B \to K\ell^+\ell^-$ and their average is $(0.39 \pm 0.06) \times 10^{-6}$. Similarly, the branching fraction for $B \to K^*(892)\ell^+\ell^-$ is also measured by both experiments with an average of $(0.94^{+0.17}_{-0.16}) \times 10^{-6}$, consistent with the SM expectation. Both experiments also measured the branching fractions for inclusive $B \to X_s\ell^+\ell^-$ decays, with an average of $(4.5 \pm 1.0) \times 10^{-6}$ [105].

Finally the decays $B^0_{(s)} \to \mu^+\mu^-$ are interesting since they only proceed at second order in weak interactions in the SM, but may have large contributions from supersymmetric loops, proportional to $(\tan\beta)^6$. CDF and D0 have both obtained results that start to exclude a portion of the region allowed by

SUSY models. The most recent limits are: $< 5.8 \times 10^{-8}$ and $< 1.8 \times 10^{-8}$, respectively, for B_s^0 and B^0 [106]. For the B_s^0 mode, the current result is just one order of magnitude above predictions. There are also limits for lepton flavor-violating channels such as $B \to e\mu$.

Summary and Outlook: The study of B mesons continues to be one of the most productive fields in particle physics. With the two asymmetric B-factory experiments Belle and BaBar, we now have a combined data sample of over 1 ab^{-1}. CP violation has been observed for the first time outside the kaon system. Evidence for direct CP violations has been observed. Many rare decays such as hadronic $b \to u$ transitions and $b \to s(d)$ gluonic penguin decays have been observed, and the emerging pattern is still full of surprises. The coming years look equally promising.

At Fermilab, CDF and D0 have accumulated about 2.5 fb^{-1}, which is the equivalent of over 10^{11} b-hadrons produced. In spite of the low trigger efficiency of hadronic experiments, a selection of modes have been reconstructed in large quantities, giving a start to a program of studies on B_s^0 and b-flavored baryons, in which a first major step has been the determination of the B_s^0 oscillation frequency.

In addition, the LHC will soon start operating and produce huge samples of b-hadrons. There are also proposals for higher-luminosity B Factories at KEK and Frascati in order to increase the samples to $\sim 50\ ab^{-1}$!

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.

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5. 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 $\phi_3 = \gamma$.
6. See the "*CP* Violation in Meson Decays" by D. Kirkby and Y. Nir in this *Review*.
7. See the "CKM Quark Mixing Matrix," by A. Cecucci, Z. Ligeti, and Y. Sakai, in this *Review*.
8. See the "Review on B-$\overline{B}$ Mixing," by O. Schneider in this *Review*.
9. See the "Determination of $|V_{cb}|$ and $|V_{ub}|$," by R. Kowalewski and T. Mannel in this *Review*.
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