PRODUCTION AND DECAY OF b-FLAVORED HADRONS

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In the two years since the last edition of this review our understanding of the physics of B mesons and b-flavored baryons has significantly improved. 1995 was another record setting year for the CLEO experiment as well as the Cornell e^+e^- storage ring (CESR) which reached an instantaneous luminosity of 3.3×10^{32} cm^{-2}s^{-1}. More than 4 fb^{-1} have been logged by the CLEO Collaboration. At CERN, the Z program has been completed and each of the four LEP experiments has recorded data samples containing about 3 million Z decays, corresponding to approximately 0.7×10^6 produced $b\overline{b}$ quark pairs. The FNAL $p\overline{p}$ collider run continued throughout most of 1995 and the CDF and DØ experiments have collected close to 100 pb^{-1} of new data. SLD has begun to contribute to B physics. Using the excellent resolution of their vertex detector they have obtained precise measurements of B-meson lifetimes. New results in this edition include:

- The first observation of exclusive semileptonic $b \to u$ transitions.
- The determination of the decay rate for inclusive $b \to s\gamma$ transitions.
- Updated lifetimes and masses for b-flavored hadrons.
- Improved measurements of B^0–$\overline{B}^0$ and B^0_s–$\overline{B}^0_s$ oscillations.
- A new set of inclusive branching ratios for B mesons.
- Updated limits on rare B decays including new results on $b \to s$ gluon.

Weak decays of heavy quarks test the Standard Model and can be used to determine its parameters, in particular the weak-mixing angles of the Cabibbo-Kobayashi-Maskawa matrix. Experiments with B mesons may lead to the first precise determination of the fourth CKM parameter, the complex phase. While the underlying decay of the heavy quark is governed by the weak interaction, it is the strong force that is responsible for the formation of the hadrons that are observed by experimenters. Hence, in order to extract the Standard Model parameters from the experimental data, an understanding of the interplay of the weak and strong interaction is needed.

Production and spectroscopy

Elementary particles are characterized by their masses, lifetimes, and internal quantum numbers. The bound states with a b quark and a $\overline{u}$ or $\overline{d}$ antiquark are referred to as the B_d ($\overline{B^0}$) and the B_u (B^-) mesons, respectively. The first radial 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^{**}.

Experimental studies of b decay are performed at the $\Upsilon(4S)$ resonance near the production threshold as well as at higher energies in proton-antiproton collisions and Z decays. For quantitative analyses of B decays the initial composition of the data sample must be known. At the threshold experiments this is determined by the ratio of charged to neutral decays of the $\Upsilon(4S)$. This ratio is denoted

$$\frac{f_+}{f_0} = \frac{\Upsilon(4S) \to B^+B^-}{\Upsilon(4S) \to B^0\overline{B}^0} \qquad (1)$$

The $\Upsilon(4S)$ resonance decays only to $B^0\overline{B}^0$ and B^+B^- pairs, while heavier states such as B_s or B_c are not accessible. The current experimental limit for non-$B\overline{B}$ decays of the $\Upsilon(4S)$ is less than 4% at the 95% confidence level [1]. CLEO has measured the production ratio using semileptonic B decays and found [2]

$$\frac{f_+}{f_0} = 1.13 \pm 0.14 \pm 0.13 \pm 0.06 \qquad (2)$$

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

At high energy collider experiments the b quarks hadronize as B_d, B_u, B_s, and B_c mesons or as baryons containing b quarks. The composition of the initial sample is not very precisely known although over the last year significant improvements have been achieved. Several methods have been developed to determine f_{B_s} and f_{Λ_b}, the fractions of B_s mesons, and b-flavored baryons produced in $Z \to b\overline{b}$ decays. ALEPH use their measurement of the product branching fraction, $f_{B_s} \times \mathrm{B}(\overline{B}^0_s \to D_s^+ \ell^- \overline{\nu}_\ell \text{ anything}) = 0.82 \pm 0.09^{+0.13}_{-0.14}\%$ [3]. Under the assumption of equal semileptonic partial widths for b-flavored hadrons results from the $\Upsilon(4S)$ experiments can be used to obtain an estimate for $\mathrm{B}(\overline{B}^0_s \to D_s^+ \ell^- \overline{\nu}_\ell)$. Using these results ALEPH [4] extract the fraction of b quarks that hadronize to B_s mesons to[†]

$$f_{B_s} = 11.1^{+2.5}_{-2.6}\% \tag{3}$$

A similar procedure is followed to obtain an estimate for the fraction of b baryons [5]:

$$f_{\Lambda_b} = 13.2 \pm 2.4 \pm 3.3\% \tag{4}$$

An alternative methods to determine f_{B_s} starts with the time integrated mixing parameter

$$\overline{\chi} = f_{B_s}\chi_s + f_{B^0}\chi_d \tag{5}$$

Assuming $\chi_s = 0.5$ and using the measured value for χ_d the fraction of B_s mesons can be extracted [6]

$$f_{B_s} = 11.3^{+2.5}_{-2.6}\% \tag{6}$$

Averaging the two measurements of f_{B_s} with correlated systematics taken into account yields

$$< f_{B_s} >= 11.2^{+1.8}_{-1.9}\% \tag{7}$$

Assuming that $f_{B^0} = f_{B^+}$ and $f_{B^0} + f_{B^+} + f_{B_s} + f_{\Lambda_b} = 1$ we obtain the results listed in Table 1.

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

b-hadron	Fraction [%]
B^+	37.8 ± 2.2
B^0	37.8 ± 2.2
B_s	$11.2^{+1.8}_{-1.9}$
Λ_b	13.2 ± 4.1

To date, the existence of four b-flavored mesons (B^-, $\overline{B}^0$, B^*, B_s) has been established. The LEP experiments have provided evidence for excited B^{**} and B_s^{**} states. The B_c is still not observed. The Λ_b baryon has been exclusively reconstructed by CDF and the LEP experiments. First indications of Σ_b and Ξ_b production have been presented by the LEP collaborations [7]. DELPHI has measured the Σ_b^*–Σ_b hyperfine splitting to 56 ± 16 MeV [8].

Lifetimes

The lifetime of a b-flavored hadron is given by its hadronic and semileptonic decay rates

$$\frac{1}{\tau_B} = \Gamma_{\rm tot} = \Gamma_{\rm hadronic} + \Gamma_{\rm semileptonic} \tag{8}$$

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 lifetimes hierarchy for b-flavored hadrons similar to 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 [9]. For the b system we expect

$$\tau(B^-) \ \geq \ \tau(\overline{B}^0) \ \approx \ \tau(B_s) \ > \ \tau(\Lambda_b^0) \tag{9}$$

Measurements of lifetimes for the various b-flavored hadrons thus provide a means to determine the importance of nonspectator mechanisms in the b sector.

The experimental errors on individual B-lifetime measurements are approaching the 5–10% level. However, in order to reach the precision necessary to test theoretical predictions, the results from different experiments need to be averaged. Using the conventional approach of weighting the measurements according to their error does not take into account the underlying exponential lifetime distribution. If a measurement fluctuates low then its weight in the average will increase, leading to a bias towards low values. Combining lifetime measurements

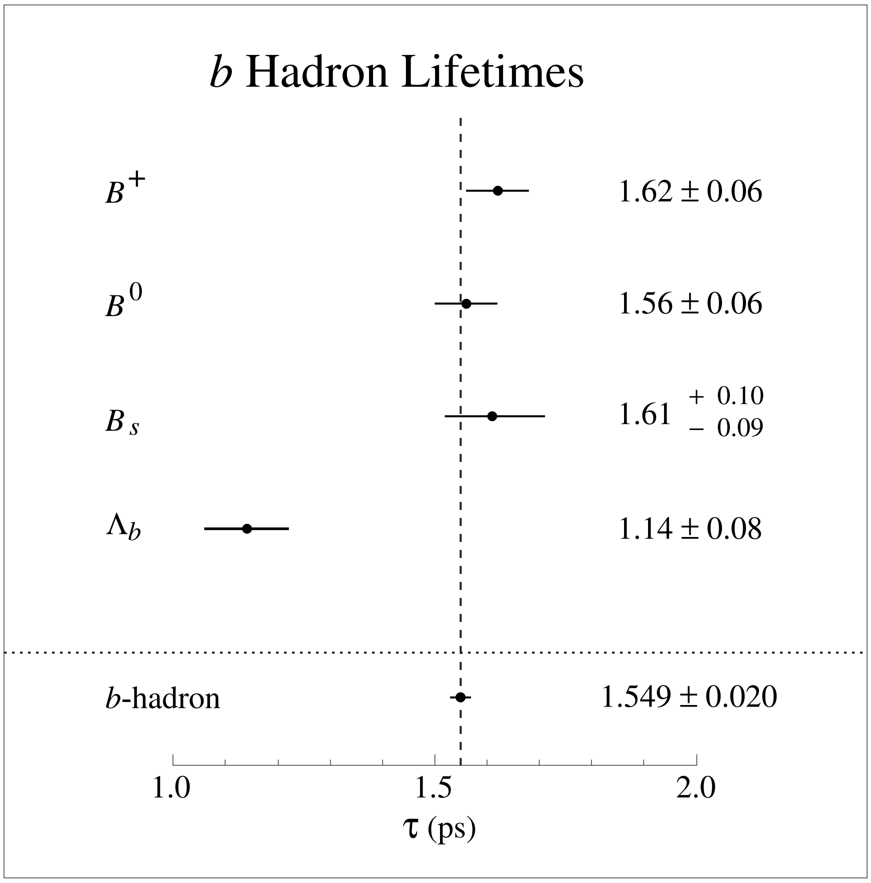

Figure 1: Summary of lifetime measurements for individual b hadrons and for the b-hadron admixture at high energy (LEP and CDF).

correctly is a difficult 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 L. Di Ciaccio (DELPHI) and the LEP B Lifetimes Working Group. Among other things, they considered uncertainties in the composition of the b sample and background, correlation in the b momentum estimation and common errors in b and c branching fractions. A detailed description of their procedures and the treatment of correlated and uncorrelated errors can be found in [10]. The experimental papers used in this calculation are given in the Particle Listing sections on b-flavored mesons and baryons. A summary of the average b-hadron lifetimes is shown in Fig. 1. The pattern of measured lifetimes follows the theoretical expectations outlined above and nonspectator effects are observed to be small. However, the Λ_b baryon lifetime is unexpectedly short. As has been noted by several authors, the observed value of the Λ_b lifetime is quite difficult to accommodate theoretically [11,12].

Semileptonic decays and mixing

Measurements of semileptonic B decays are important for the determination of the weak couplings $|V_{cb}|$ and $|V_{ub}|$ and test our understanding of the dynamics of heavy quark decay. A measurement technique using events with two leptons was introduced by the ARGUS experiment [13] which significantly reduces the model dependence associated with the subtraction of the $b \to c \to \ell$ cascade component. A high momentum lepton is selected ($p_\ell > 1.4$ GeV) which tags a $b\overline{b}$ event. This primary lepton is then combined with an additional lepton candidate which has a momentum above 0.5 GeV. In the absence of mixing, if the second lepton has a charge opposite to the tagging lepton it is a primary lepton from the b decay, while if the second lepton has the same sign as the tag it is a cascade lepton. Models of semileptonic B decay are only needed for the small extrapolation to zero lepton momentum. Using this method, CLEO II finds

$$\mathrm{B}_{\mathrm{sl}} \;=\; (10.49 \,\pm\, 0.17 \,\pm\, 0.43)\,\% \tag{10}$$

consistent with the conventional single lepton analysis.

Assuming the semileptonic decay width is the same for all b-flavored hadrons, the semileptonic branching ratio should be slightly different at LEP since other b particles are produced:

$$\mathrm{B}_{\mathrm{sl}}(\Upsilon(4S)) \;=\; \frac{\Gamma_{\mathrm{sl}}}{\Gamma_{\mathrm{tot}}} \;=\; \Gamma_{\mathrm{sl}} \times \frac{(\tau_{B^+} + \tau_{B^0})}{2} \tag{11}$$

while

$$\mathrm{B}_{\mathrm{sl}}(Z) \;=\; \Gamma_{\mathrm{sl}} \times \tau_b \tag{12}$$

Using the world averages for the B lifetimes and the CLEO semileptonic branching fraction this gives

$$\mathrm{B}_{\mathrm{sl}}(Z) = \frac{2\tau_b}{(\tau_{B^+} + \tau_{B^0})} \times \mathrm{B}_{\mathrm{sl}}(\Upsilon(4S)) = 10.2 \pm 0.4\% \tag{13}$$

Note that the contribution of other hadrons *reduces* the expected average semileptonic branching fraction at the Z. This is below the experimental average from LEP, $\mathrm{B_{sl}}(Z) = 10.9 \pm 0.1 \pm 0.3$, but the errors are still too large to draw any conclusions.

It is interesting to compare the inclusive semileptonic branching fraction to the sum of branching fractions for exclusive modes. CLEO and the LEP collaborations have updated their measurements of $\mathrm{B}(B \to D\ell\nu_\ell)$ and $\mathrm{B}(B \to D^*\ell\nu_\ell)$. Including the recent observations of $B \to D^{**}(2420)\ell\nu_\ell$ and $B \to D^{**}(2460)$ by OPAL and ALEPH the sum of exclusive semileptonic branching fractions amounts to $8.81 \pm 0.1\%$. The remaining decays may correspond to $B \to D^{**}\ell\nu_\ell$ where D^{**} denotes a p-wave charmed meson with a large width (*e.g.* the very broad but as of now unobserved $1^3P_1(2490)$ and $1^3P_0(2440)$ states). It is also possible that the other missing decays are $B \to D\pi\ell^-\nu_\ell$ where the $D\pi$ system is nonresonant or originates from the decay of a broad excited charm meson. These possibilities are difficult to check experimentally. It is also conceivable that the difference between the sum of the exclusive modes and the inclusive semileptonic rate is due to a systematic error in the D meson absolute branching fraction scale.

The ALEPH, DELPHI, OPAL, and CDF experiments have performed explicit measurements of $\mathrm{Prob}(B^0 \to \overline{B^0})$ as a function of time to obtain the parameter $x_d = \Delta m_d/\Gamma$ [6]. The initial state b quark flavor is tagged either using leptons or jet charge, while the flavor of the final state b quark is tagged using either $\overline{B}_d \to D^{*+}\ell^-X$, $\overline{B}_d \to D^{*+}X$, or $\overline{B}_d \to \ell^-X$. If the final state is not fully reconstructed, as is the case for the analyses using dileptons, then the decay time must be determined using a topological vertexing technique where the lepton from the B decay and the other tracks in the same jet hemisphere are combined. The boost is determined using the observed energy, missing momentum and a correction factor determined from a Monte Carlo simulation. Averaging these results gives $\Delta m_d = 0.458 \pm 0.020\ \mathrm{ps}^{-1}$ which is statistically superior to the results obtained from time integrated measurements by experiments at the $\Upsilon(4S)$.

The measurement of the mixing parameter $x_s = \Delta m_s/\Gamma$ for the B_s meson combined with the results on B^0–$\overline{B}^0$ oscillations allows the determination of the ratio of the CKM matrix elements $|V_{td}|^2/|V_{ts}|^2$ with significantly reduced theoretical uncertainties. Experimentally the measurement of x_s is a challenge. For large values, as expected for the B_s meson, time integrated measurements of B_s mixing become insensitive to x_s and one must make time dependent measurements in order to extract this parameter. These are very difficult because of the rapid oscillation rate of the B_s meson. Using an event sample with a lepton and a tag based on a jet charge technique where each track is weighted by its rapidity, ALEPH has searched for a high frequency component in their fit to the proper time distribution. They find $\Delta m_s > 6$ ps^{-1} or $x_s > 8.8$ at the 95% confidence level [6].

Hadronic decays

CLEO has presented a set of new measurements of inclusive B-meson decay rates that can be used to test the parton level expectation that most B decays proceed via a $b \to c$ transition. If we neglect the small contributions from $b \to u$ and penguin transitions, we expect about 1.15 charm quarks to be produced per B decay. The additional 15% is due to the fact that the virtual W forms a $s\bar{c}$ quark pair with a probability of approximately 0.15. This expectation can be verified experimentally by adding all inclusive $b \to c$ branching fractions. Using the world averages for the $b \to c$ branching fractions we find [14]:

$$
\begin{aligned}
\text{Charm yield} &= \mathrm{B}(B \to D^0 X) + \mathrm{B}(B \to D^+ X) + \mathrm{B}(B \to D_s X) \\
&+ \mathrm{B}(B \to \Lambda_c X) + \mathrm{B}(B \to \Xi_c^+ X) + \mathrm{B}(B \to \Xi_c^0 X) \\
&+ 2 \times \mathrm{B}(B \to \psi X) + 2 \times \mathrm{B}(B \to \psi' X) \\
&+ 2 \times \mathrm{B}(B \to \chi_{c1} X) + 2 \times \mathrm{B}(B \to \chi_{c2} X) \\
&+ 2 \times \mathrm{B}(B \to \eta_c X \ \text{(incl. other } c\bar{c})) \\
&= 1.15 \pm 0.05 \qquad (14)
\end{aligned}
$$

The factor of 2 which multiplies $\mathrm{B}(B \to c\overline{c}X)$ accounts for the two charm quarks produced in $b \to c\overline{c}s$ transitions. Wherever possible the branching fractions for direct production are used. The contribution of $B \to \eta_c X$ and other charmonia is generously taken to be at the CLEO 90% confidence level upper limit $\mathrm{B}(B \to \eta_c X) < 0.90\%$.

Another interesting quantity is the fraction of B decays in which two charm quarks are produced. In a parton level calculation, Palmer and Stech [15] find that $\mathrm{B}(B \to X_{c\overline{c}}) = 19 \pm 1\%$ where the theoretical error is the uncertainty due to the choice of quark masses. This can be compared to the sum of the experimental measurements [14]

$$\begin{aligned}
\mathrm{B}(B \to X_{c\overline{c}}) &= \mathrm{B}(B \to D_s X) + \mathrm{B}(B \to \psi X) + \mathrm{B}(B \to \psi' X) \\
&+ \mathrm{B}(B \to \chi_{c1} X) + \mathrm{B}(B \to \chi_{c2} X) + \mathrm{B}(B \to \Xi_c X) \\
&+ \mathrm{B}(B \to \eta_c X \ \text{(incl. other } \overline{c})) \\
&= (15.8 \pm 2.8)\% \qquad (15)
\end{aligned}$$

where the direct $B \to \psi$ and $B \to \chi_{c1}$ branching fraction have been used. The contribution from $B \to \Xi_c^0 X$ is reduced by 1/3 to take into account the fraction that is not produced by the $b \to c\overline{c}s$ subprocess but by $b \to c\overline{u}d + s\overline{s}$ quark popping.

A possible contribution of $B \to D\overline{D}KX$ decays, which corresponds to the quark level process $b \to c\overline{c}s$ with popping of a light quark pair, is not included in the sum calculated above. Buchalla, Dunietz, and Yamamoto have recently suggested that the latter mechanism may be significant [16]. This possibility leads to wrong sign D–ℓ correlations and is currently under investigation at CLEO. Preliminary results [17] indicate a significant branching fraction on the order of 10% for $B \to \overline{D}_{\text{upper vertex}} X$.

The charm yield per B-meson decay is related to an intriguing puzzle in B physics: the experimental value for the semileptonic branching ratio of B mesons is significantly below the theoretical lower bound $\mathrm{B} > 12.5\%$ from QCD calculations within the parton model [18]. An enhanced hadronic decay rate would resolve this discrepancy and several explanations have been proposed. The theoretically preferred solution calls for an enhancement of the $b \to c\bar{c}s$ channel [19]. Increasing the $b \to c\bar{c}s$ component, however, would increase the average number of c quarks produced per b-quark decay and lead to another interesting problem: the predicted number of charm quarks per b decay would rise to 1.3 while the current experimental value for this number is 1.15 ± 0.05. Moreover, as noted above, $\mathrm{B}(B \to X_{c\bar{c}}) = 15.8 \pm 2.8$ is far below the required 30%. A systematic study of inclusive hadronic B decays to mesons and baryons and more precise measurements of charm meson branching fractions will be required to resolve this problem.

Measurements of exclusive hadronic B decays have reached sufficient precision to challenge our understanding of the dynamics of these decays. The factorization hypothesis has been experimentally confirmed for decays with large energy release. By comparing hadronic B^- and $\overline{B}^0$ decays, the relative contributions from external and internal spectator decays have been disentangled. For all decay modes studied the B^- branching ratio was found to be larger than the corresponding $\overline{B}^0$ branching ratio indicating constructive interference between the external and internal spectator amplitudes. This came as a surprise since destructive interference was observed in hadronic charm decay. However, the B^- modes analyzed so far comprise only a small fraction of the total hadronic rate. Further experimental study is required to determine at what level constructive interference is present in the remainder of hadronic B^- decays.

Rare decays

All B meson decays that do not occur through the usual $b \to c$ transition are known as rare B decays. The simplest diagram for a rare B decay is obtained by replacing the $b \to c$ transition by a CKM suppressed $b \to u$ transition. These decays probe the small CKM matrix element V_{ub}, the magnitude of which sets bounds on the combination $\rho^2 + \eta^2$ in the Wolfenstein parameterization of the CKM matrix. So far the only measurement of the magnitude of V_{ub} has been obtained from measurements of inclusive semileptonic B decays [20]. Last year CLEO reported the observation of exclusive semileptonic transitions. Using their large data sample and employing the excellent hermiticity of the CLEO II detector they were able to measure (using the BSW model) B($B^0 \to \pi^- \ell^+ \nu_\ell$) = $(1.63 \pm 0.46 \pm 0.34) \times 10^{-4}$ and B($B^0 \to \rho^- \ell^+ \nu_\ell$) = $(3.88 \pm 0.54 \pm 0.34) \times 10^{-4}$ [21].

While the errors are still large these results are an important step towards establishing a reliable value of $|V_{ub}|$.

Exclusive hadronic $b \to u$ transitions still await experimental discovery. CLEO sees a significant signal in the combined $B^0 \to \pi^+\pi^-$, $K^+\pi^-$ channels but detector resolution and statistics are not sufficient to separate the two modes.

The observation of the decay $B \to K^*(892)\gamma$, reported in 1993 by the CLEO II experiment, provided first evidence for the 1-loop penguin diagram [22]. The observed branching fractions were used to constrain a large class of Standard Model extensions [23]. However, due to the uncertainties in the hadronization, only the inclusive $b \to s\gamma$ rate can be reliably compared with theoretical calculations. This rate can be measured from the endpoint of the inclusive photon spectrum in B decay. CLEO found B($b \to s\gamma$) = $(2.32 \pm 0.54 \pm 0.35) \times 10^{-4}$.

A larger total rate is expected for gluonic penguins, the counterpart of $b \to s\gamma$ with the photon replaced by a gluon. However, it is a major experimental challenge to measure the inclusive $b \to sg$ rate, where the virtual gluon hadronizes as a $q\overline{q}$ pair. Since the coupling of gluons to quark-antiquark pairs is flavor independent, it is expected that except for modifications due to phase space $b \to s\overline{s}s$ will be comparable to $b \to s\overline{u}u$, $b \to s\overline{d}d$. A recent CLEO search revealed no signal for exclusive $b \to s\overline{s}s$ decays such as $\overline{B} \to \phi K^{(*)}$ nor did they find an excess in the endpoint of the ϕ momentum spectrum for inclusive $B \to \phi$ transitions.

Outlook

With the end of the Fermilab collider run and the change of the LEP beam energies CLEO and SLD will be the only collider experiments in the next few years to collect data. While this might slow down the current rate of rapid progress in our understanding of heavy flavor physics there are still many answers hidden in the large data samples collected by CDF and the LEP collaborations. This combined with the ever-growing CLEO data sample will provide many new insights into all aspects of B physics.

The one exception is a measurement of the complex phase in CKM matrix. Data samples at least one order of magnitude larger than those available at present are needed to observe CP asymmetries in the B-meson system and to perform one of the most fundamental consistency check of the Standard Model. This is the justification for the construction of high luminosity e^+e^- storage rings (PEP II/BaBar, CESR III/CLEO III, TRISTAN II/BELLE) as well as a dedicated fixed target experiment at the HERA ring at DESY. Hadron collider experiments dedicated to the study of CP violation have also been proposed at Fermilab and at CERN.

Notes and References

† The results given in this section have been obtained by O. Hayes (ALEPH) and M. Jimack (OPAL). Their analysis is based on the average branching ratio, mixing parameters, and lifetimes listed in this compilation.

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