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Experimental status of B physics

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Abstract. In a short period of time, we will have a large amount of results from B-factories including ones on CP violation. In this talk, we briefly review the current experimental status of B-physics. After a quick description of b-facilities, we divide this vast field into two categories: (1) weak interaction and QCD, (2) unitarity triangle and CP violation. Only a few critical items are selected in each category for the sake of time and space.

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1. B facilities

There are several B-physics facilities currently operational, and they can be divided into e^+e^- colliders and hadron machines. For the hadron machines, CDF and D0 at Fermilab have finished data taking for Run 1 and now gearing up for Run 2 to begin in fall 2000, and at DESY, HERA-B is getting ready to take data for the proton beam of the e^-p collider impinging on a wire target. In the future, the general purpose detectors ATLAS and CMS will start studying B-physics when LHC commences its operation, and a dedicated B-physics detector LHCb will begin at the same time. On the north American continent, the BTeV experiment is scheduled to start operation at about the same time.

LEP is a e^+e^- collider which has run on Z^0 and the LEP experiments ALEPH, DELPHI, L3, OPAL have generated rich results on B physics many of which are covered in this review. At this point, however, no further run is planned on the Z^0 peak. Currently, three e^+e^- B-physics experiments are running: CLEO at CESR (Cornell), BaBar at PEP-II (SLAC), and Belle at KEK-B (Japan). All these machines are mainly designed to create $\Upsilon 4S$ resonance ($M_{\Upsilon 4S}$ =10.58 GeV) which decays to B^+B^- and $B^0\bar{B}^0$ where B mesons are nearly at rest in the rest frame of $\Upsilon 4S$ ($\beta_B \sim 0.06$). CESR collides e^+ and e^- with symmetric energies where each energy is half the $\Upsilon 4S$ mass, namely 5.29 GeV. In this scheme, the B mesons are nearly at rest in the laboratory frame, and as a result one cannot easily measure the B decay time by measuring the decay distance. PEP-II and KEK-B thus collides e^+ and e^- at different energies where the center of mass energy is kept at the $\Upsilon 4S$ mass:

$$E_{\rm CM} = 2\sqrt{E_{e^+}E_{e^-}}\,, \tag{1}$$

Table 1. Parameters of e^+e^- B-factories.

Machine	CESR	PEP-II	KEK-B
Detector	CLEO	BaBar	Belle
Circumference (km)	0.768	2.199	3.016
# of rings	1	2	2
E_{e^+}(GeV)	5.3	3.1	3.5
E_{e^-}(GeV)	5.3	9.0	8.0
$\beta_{\Upsilon 4S}$	~ 0	0.49	0.39
Crossing angle (mrad)	±2.3	0	±11
Luminosity (cm^{-2}s^{-1})	1.5×10^{33}	3×10^{33}	10^{34}
$\# B\bar{B}/s$	1.5	3	10
	Achievements so far		
Lum (peak)	8×10^{32}	1.9×10^{33}	1.8×10^{33}
$\int L\mathrm{d}t$ (fb^{-1})	9.2	6	2.7

then the $\Upsilon 4S$ will be moving with velocity given by

$$\beta_{\Upsilon 4S} = \frac{P_{\Upsilon 4S}}{E_{\Upsilon 4S}} = \frac{E_{e^-} - E_{e^+}}{E_{e^-} + E_{e^+}} . \tag{2}$$

Basic parameters of the e^+e^- B-factories are given in table 1. In particular, one B lifetime corresponds to 250 μm for BaBar and 200 μm for Belle. If energies of two beams are different, two separate beamlines are needed; one each for e^+ and e^-.

Apart from the beam energies, a main difference among the machines are the ways two beams are separated. Since there is a limit to how many particles can be pushed into a bunch, the number of bunches needs to be increased in order to obtain high luminosity. This makes the bunch spacing to be small (of order 60 cm) and causes unwanted parasitic crossing unless two beams are separated except at the interaction point. CESR accomplishes this by using a pair of intertwining orbits called pretzel orbits within a single ring. The e^+ and e^- bunches pass each other only where two orbits are separated (except at the interaction point). At the interaction point, two beams cross with a finite crossing angle of ±2.3 mrad. KEK-B uses a large crossing angle of ±11 mrad which is enough to separate the two beams. PEP-II employs head-on collision but uses bending magnets near the interaction point where two beams of different energies bend with different radii thereby separating the two beams. CLEO has recently started to run with an upgraded detector (CLEO-III), and both BaBar and Belle are well on their way to achieve the design luminosities.

2. Weak interaction and QCD

2.1 *Inclusive hadronic rates and semileptonic branching ratio*

Introduction: Around 1994, it was pointed out [1,2] that the theoretical prediction of the semileptonic branching fraction $B_{\mathrm{s.l.}}$ is too large compared to the experimental value. The discrepancy was particularly stark when viewed in the two-dimensional plane of n_c vs $B_{\text{s.l.}}$, where n_c is the average number of charm or anticharm created per B decay [1–3]. This was because when the uncertainties of the theory, in particular the charm quark mass, were tweaked to reduce $B_{\text{s.l.}}$, it increased the inclusive non-leptonic decay rates which resulted in too large a value for n_c compared to measurement.

The ingredients of the theoretical estimation of $B_{\text{s.l.}}$ and n_c are the local quark-hadron duality and the perturbative QCD (pQCD) in the framework of operator product expansion (OPE) [4] as well as heavy quark expansion (HQE) [5]. The essential point of the local quark-hadron duality is the assumption that the sum of actual hadronic final states with certain quark flavor contents is equal to the same flavor contents at the quark level, and that it holds for a given c.m. energy of the hadronic system (i.e. 'local'). HQE gives the total rate $B \to f$ expressed as

$$\Gamma(B \to f) = \Gamma_0 \left[a \left(1 + \frac{\lambda_1}{2m_b^2} + \frac{3\lambda_2}{2m_b^2} \right) + b\frac{\lambda_2}{m_b^2} + \mathcal{O}\left(\frac{1}{m_b^3} \right) \right], \tag{3}$$

where $\Gamma_0 = G_F^2 m_b^5 / 192\pi^3$, the parameters a, b contain CKM factors, Wilson coefficients (evaluated using pQCD) and phase space factors. Non-perturbative effects are included in $\lambda_{1,2}$, where $\lambda_1 = 0 \sim -0.7$ GeV^2 is the time-delation effect by the Fermi motion of the b quark inside a hadron, and $\lambda_2 = (1/4)(m_B^{*2} - m_B^2) = 0.12$ GeV^2 is the chromomagnetic effect. Total effect by $\lambda_{1,2}$ amounts to a few % increase of the hadronic rate. It should be noted that not all non-perturbative effects are included in $\lambda_{1,2}$. Table 2 summarizes rough sizes of the various corrections for $B_{\text{s.l.}}$ and n_c [6–8]. The parameter r_x represents the rate $b \to x$ normalized to the semileptonic rate $\Gamma_{\text{s.l.}}$.

Note the increase of about 30% in $r_{c\bar{u}d}$ and $r_{c\bar{c}s}$ due to the next-to-leading (NLO) correction and a large increase of $r_{c\bar{c}s}$ when the finite charm mass is included.

Measurement of $B_{\text{s.l.}}$ *and* n_c: On $\Upsilon(4S)$, the state of the art is the charge correlation method where one B is tagged by a high momentum lepton and another lepton with opposite sign is searched for on the 'other side'. This rejects the cascade leptons $b \to c \to \ell^+$. Corrections are still needed for the B mixing and the wrong-sign charm $b \to \bar{c} \to \ell^-$ which mimics the signal $b \to \ell^-$. The CLEO result is $B_{\text{s.l.}} = 10.49 \pm 0.46\%$ [9], and the particle data group [10] cites the average $\Upsilon(4S)$ $B_{\text{s.l.}} = 10.45 \pm 0.21\%$.

Measurements of $B_{\text{s.l.}}$ on Z^0 are summarized in table 3.

Table 2. Effects of various corrections affecting $B_{\text{s.l.}}$ and n_c.

	Naive	NLO ($m_c = 0$)	NLO ($m_c \neq 0$)
$r_{c\ell\nu}$	2.22	2.22	2.22
$r_{c\bar{u}d}$	3.0	4.0	4.0
$r_{c\bar{c}s}$	1.2	1.6	2.1
$B_{\text{s.l.}}$	0.16	0.13	0.12
n_c	1.16	1.17	1.21
$Br_{c\bar{c}s}$	0.18	0.20	0.25
		($r_{no\,c} \sim 0.2 \pm 0.1$)	

Table 3. Measurements of $B_{\rm s.l.}$ at LEP. (a) b-Tag by lifetime and fit neural-net variables to separate $b \to \ell^-$, $b \to c \to \ell^+$, and backgrounds. (b) See text.

Experiment	$B_{\rm s.l.}$(%)	method
ALEPH 95 [11]	$11.01 \pm 0.10 \pm 0.30$	$1\ell + 2\ell$
L3 96 [12]	$10.68 \pm 0.11 \pm 0.46$	e, μ, ν
OPAL 99 [13]	$10.83 \pm 0.10 \pm 0.20^{+0.20}_{-0.13}$	(a)
DELPHI 99 [14]	$10.65 \pm 0.07 \pm 0.25^{+0.28}_{-0.12}$	(b)

Table 4. Measurements of n_c using explicit charm hadron counting.

(%)	CLEO 98 [15]	ALEPH 96 [16]	OPAL 96 [17]	DELPHI 99 [18]
D^0	63.6±3.0	60.5±3.6	53.5±4.1	60.05±4.29
D^+	23.5±2.7	23.4±1.6	18.8±2.0	23.01±2.13
D_s^+	11.8±1.7	18.3±5.0	20.8±3.0	16.65±4.50
Λ_c	3.9±2.0	11.0±2.1	12.5±2.6	8.90±3.00
$\Xi_c^{0,+}$	2.0±1.0	6.3±2.1	–	4.00±1.60
$(c\bar{c})$	5.4±0.7	3.4±2.4	–	4.00±1.29
n_c	1.10±0.05	1.23±0.07		1.17±0.09

There are two recent results from OPAL and DELPHI. DELPHI has combined four methods: (1) 1ℓ and 2ℓ samples are used without flavor tagging, (2) b-tag by lifetime and lepton and a fit was applied to p_ℓ in the B c.m. system and the charge correlation of the tagged flavor and the lepton charge, (3) a multi-variate fit was applied to all hadronic events, (4) similar to 2 where a neural net was used for flavor identification.

The charm count n_c can be obtained by explicitly counting the charm hadrons $D^0, D^+, D_s^+, \Lambda_c$ and Ξ_c created in a b decay. Charmonia decayed by $c\bar{c}$ annihilation are counted as two each. The results are shown in table 4.

For Ξ_c, ALEPH and DELPHI used the CLEO measurement of Br$(B \to \Xi_c)$ and added Br$(\Lambda_b \to \Xi_c)$ prediction by JETSET. However, the value used by ALEPH Br$(B \to \Xi_c) = 3.9 \pm 1.5\%$ [19] is now superseded by Br$(B \to \Xi_c) = 2.0 \pm 1.0\%$ [19] which is used correctly by DELPHI.

DELPHI [20] also used the vertex information to extract the numbers of 0-charm, 1-charm, and 2-charm events from which n_c can be extracted, which gave $n_c = 1.147 \pm 0.041 \pm 0.008$. We make the average of LEP values after appropriate corrections discussed above to obtain $n_c = 1.16 \pm 0.04$ (LEP average). Figure 1 shows the comparison with theory and experiments. $B_{\rm s.l.}$ for Z^0 is converted to $\Upsilon 4S$ value by multiplying the ratio τ_B/τ_b to account for the different mixture of b hadrons. The discrepancy in $B_{\rm s.l.}$ between the Z^0 value and the $\Upsilon(4S)$ value is quite alarming while the theory and experimental values on Z^0 are consistent. Thus, the answer to the question ‘Did pQCD and HQE work well for the inclusive hadronic rate?’ is mixed.

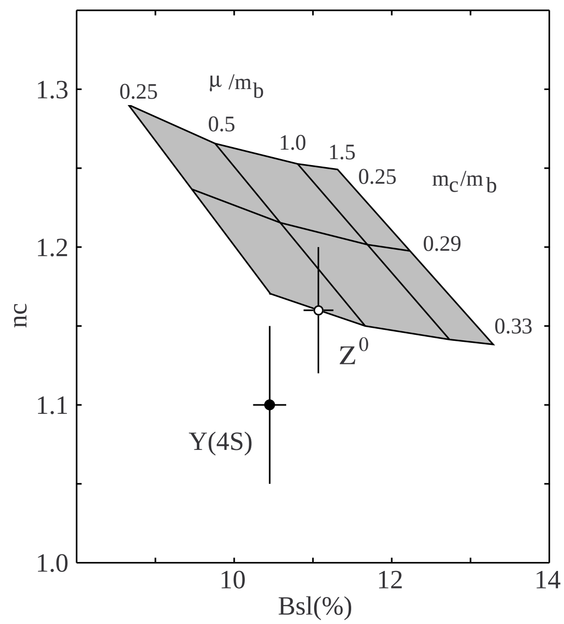


Figure 1. $B_{\rm s.l.}$ vs n_c. Theory vs experiments.

3. Radiative decays $b \to s\gamma$

3.1 *Inclusive rate of* $b \to s\gamma$

This is a story of triumph for pQCD. The relevant effective Hamiltonian is given by

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1,2,7,8} C_i(\mu) O_i(\mu)\,, \tag{4}$$

where C_i are the Wilson coefficients calculated by pQCD and

$$O_1 = (\bar{c}_{L\beta}\gamma^\mu b_{L\alpha})(\bar{s}_{L\alpha}\gamma_\mu b_{L\beta}), \quad O_2 = (\bar{c}_{L\alpha}\gamma^\mu b_{L\alpha})(\bar{s}_{L\beta}\gamma_\mu b_{L\beta}),$$
$$O_7 = \frac{em_b}{16\pi^2}\bar{s}_\alpha \sigma^{\mu\nu}(1+\gamma_5) b_\alpha F_{\mu\nu}, \quad O_8 = \frac{g_s m_b}{32\pi^2}\bar{s}_\alpha \sigma^{\mu\nu}(1+\gamma_5)\lambda^a_{\alpha\beta} b_\beta G^a_{\mu\nu}\,. \tag{5}$$

At the lowest level, there is O_7 only and the QCD correction is found to increase the rate by about a factor of three. Now the complete NLO calculation has been performed and the scale dependence reduced from $\sim$ 20% (LO) to $\sim$ 5% (NLO). The non-perturbative effects due to $\lambda_{1,2}$ was found to increase the rate by about 3%.

The experimental values are compared to the theoretical value in table 5. CLEO looked for an excess of single photon at the end of point of B decay, and the continuum background was suppressed by the so-called 'pseudo B reconstruction' technique where all possible combinations $\gamma + 1K^{0,+} + n^+\pi^\pm + n^0\pi^0$ $(n^+ + n^0 \leq 4$ and $n^0 \leq 1)$ were checked and if there is at least one combination that is consistent with B decay, then the energy of the γ was plotted. The agreement of theory and experiment is excellent which is particularly impressive since the QCD correction boosted the theoretical value by a factor of three. In the analysis by CLEO, the pseudo B reconstruction provides a method of flavor tag as a bonus with a mistag rate of about 8%. This allows a measurement of $b - \bar{b}$ asymmetry:

$$A_{\rm CP} \equiv \frac{b - \bar{b}}{b + \bar{b}} = (+0.16 \pm 0.14 \pm 0.05)(1 \pm 0.04) \text{ or } -0.09 < A_{\rm CP} < 0.42\,, \qquad (6)$$

where the last error is due to mistag and the limits are 90% c.l. The CLEO data is based on $3\,\text{fb}^{-1}$ of data and a new result with three times the data should appear sometime soon.

3.2 *Exclusive $b \to s\gamma$ modes*

Experimental numbers for the exclusive radiative B decays by CLEO [24] are shown in table 6. The ratio Br$(K_2^*(1430)\gamma)/$Br$(K^*\gamma) = 0.39^{+0.15}_{-0.13}$ may be compared to theoretical predictions of 3.0–4.9 [25] and 0.4 ± 0.2 [26]. Assuming Br$(\rho^+\gamma) = 2$Br$(\rho^0\gamma) = 2$Br$(\omega\gamma)$, the upper limits on Br$(\rho\gamma)/$Br$(K^*(890)\gamma)$ can be used to extract an upper limit on $|V_{td}/V_{ts}|$:

$$\left|\frac{V_{td}}{V_{ts}}\right| < 0.75 \qquad \text{(90\% c.l.)}\,. \qquad (7)$$

Table 5. Inclusive rate $b \to s\gamma$; experiments vs theory.

	Br($b \to s\gamma$) ($\times 10^{-4}$)
CLEO [21]	3.15 ± 0.35 (stat) ± 0.32 (sys) ± 0.26 (model)
ALEPH [22]	3.11 ± 0.80 (stat) ± 0.72 (sys)
Theory [23]	3.28 ± 0.33

Table 6. Exclusive $b \to s\gamma$ modes from CLEO. Upper limits are 90% c.l.

Mode	Detection	Br($\times 10^{-5}$)
$B^+ \to K^{*+}\gamma$	$K^{*+} \to K^+\pi^0, K^0\pi^+$	$4.55^{+0.72}_{-0.68} \pm 0.34$
$B^0 \to K^{*0}\gamma$	$K^{*0} \to K^+\pi^-, K^0\pi^0$	$3.76^{+0.89}_{-0.83} \pm 0.28$
$B^0 \to K_2^*(1430)\gamma$	$K^* \to K\pi$	$1.66^{+0.59}_{-0.53} \pm 0.13$
$B^0 \to \omega\gamma$	$\omega \to \pi^+\pi^-\pi^0$	< 0.92
$B^0 \to \rho^0\gamma$	$\rho^0 \to \pi^+\pi^-$	< 1.7
$B^+ \to \rho^+\gamma$	$\rho^+ \to \pi^+\pi^0$	< 1.3
$B^0 \to \phi\gamma$	$\phi \to K^+K^-$	< 0.33

In addition, all K^* modes except for $K^0\pi^0$ can be used to tag the b flavor. The CP asymmetry thus obtained is

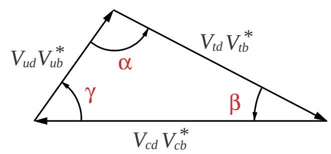
$$A_{\rm CP}(K^*\gamma) = +0.080 \pm 0.125\,. \tag{8}$$

The expected asymmetry in the standard model is quite small ($\sim$ 1%).

4. Unitarity triangle and CP violation

The unitarity condition of the d-column and b-column of the CKM matrix is written as

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\,. \tag{9}$$



The three angles $\alpha(\phi_2)$, $\beta(\phi_1)$, and $\gamma(\phi_3)$ are often defined as

$$\alpha \equiv \arg\left(\frac{V_{td}V_{tb}^*}{-V_{ud}V_{ub}^*}\right)\,,\ \beta \equiv \arg\left(\frac{V_{cd}V_{cb}^*}{-V_{td}V_{tb}^*}\right)\,,\ \gamma \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{-V_{cd}V_{cb}^*}\right)\,, \tag{10}$$

and by definition satisfies $\alpha+\beta+\gamma = \pi$ mod(2π) regardless of if the triangle is closed (i.e. if the CKM matrix is unitary or not). If the sum does not add up to the expected value, it simply means that the measured quantities are not as defined. Thus, it is critical to measure the sizes of the triangle as well as the angles to test the unitarity of the CKM matrix.

4.1 *Exclusive semileptonic decays*

The exclusive semileptonic decays $B \to D^{*0,+}\ell\nu$ can be used to extract $|V_{cb}|$ using the expression

$$\frac{{\rm d}\Gamma}{{\rm d}w} = \frac{G_F^2|V_{cb}|^2 F_D(w)^2}{48\pi^3}(m_B+m_D)^2 m_D^3 (w^2-1)^{3/2}\,, \tag{11}$$

where w is the boost γ-factor of D in the B frame, and $F_D(1)$ is the form factor at zero recoil ($w = 1$) which is predicted to be unity in the heavy-quark limit. Namely, the rate is plotted as a function of w and then the extrapolation to $w = 1$ is used to extract $|V_{cb}|$. Recent result by CLEO is

$$\begin{aligned}
&{\rm Br}(\bar{B}^0 \to D^+\ell\nu) = 2.09 \pm 0.13 \pm 0.18\%,\\
&{\rm Br}(B^- \to D^0\ell\nu) = 2.21 \pm 0.13 \pm 0.19\%,\\
&|V_{cb}|F_D(1) = 0.0416 \pm 0.0047 \pm 0.0037,\\
&|V_{cb}| = 0.042 \pm 0.005 \pm 0.004 \pm 0.004.\\
&\qquad {\scriptstyle (F_D(1)=1.0\pm 0.1 \text{ used})}
\end{aligned} \tag{12}$$

$B \to D^{*0,+}\ell\nu$ can also be used to extract $|V_{cb}|$. A slightly old set of results from CLEO reads

$$|V_{cb}|F(1) = 0.0351 \pm 0.0019 \pm 0.0018,$$
$$|V_{cb}| = 0.0383 \pm 0.0021 \pm 0.0020 \pm 0.0011. \tag{13}$$

The value of $|V_{cb}|$ can also be extracted from the inclusive $b \to c\ell\nu$ rate assuming the quark-hadron duality. Recently, LEP results were combined to give

$$|V_{cb}| = \begin{cases} (40.8 \pm 0.4 \pm 2.0) \times 10^{-3} & \text{(Inclusive)} \\ (38.4 \pm 2.5 \pm 2.2) \times 10^{-3} & \text{(Exclusive)} \\ (40.2 \pm 1.9) \times 10^{-3} & \text{(Combined)} \end{cases} \tag{14}$$

The agreement between inclusive and exclusive results are good, and indicates the validity of the (global) quark-hadron duality.

Similarly, the charmless semileptonic rate $b \to u\ell\nu$ can be used to extract $|V_{ub}|$. A combined result of ALEPH, DELPHI, and L3 is

$$\mathrm{Br}(b \to u\ell\nu) = \left(1.67 \pm 0.35 \pm 0.38 \pm \underset{\text{model}}{0.20}\right) \times 10^{-3},$$

$$|V_{ub}| = \left(4.05^{+0.39+0.43+0.23}_{-0.46-0.51-0.27} \pm \underset{\tau_B}{0.02} \pm \underset{\text{Theory}}{0.16}\right) \times 10^{-3}. \tag{15}$$

CLEO has recently updated the exclusive $B^0 \to \rho^-\ell^+\nu$ measurement [27]. Combined with the previous CLEO measurement [28], one obtains

$$\mathrm{Br}(B \to \rho^-\ell\nu) = (2.57 \pm 0.29^{+0.33}_{-0.46} \pm 0.41) \times 10^{-4},$$
$$|V_{ub}| = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55(th.)) \times 10^{-3}\,, \tag{16}$$

which is smaller than the LEP number above but statistically consistent.

4.2 *Neutral B mixing*

The probability χ for a meson created as B^0 to decay as $\bar{B}^0$ is $\chi = \frac{1}{2}x^2/(1+x^2)$ where $x = \Delta m/\Gamma$. Here, B^0 is B_d or B_s. The mass difference δm is given by

$$\Delta m_q = \frac{g^4}{192\pi^2 m_W^2}|V_{tb}|^2|V_{tq}|^2 f_{B_q}^2 B_{B_q}^2 \eta_{\mathrm{QCD}} f(m_t), \qquad (q = d \text{ or } s) \tag{17}$$

where the 'bag factor' B_q and the decay constant f_{B_q} are major source of theoretical uncertainties. Experimental values [29] leads to

$$\Delta m(B_d) = 0.471 \pm 0.016\ \mathrm{ps}^{-1}\,, \quad \Delta m(B_s) > 14.3\ \mathrm{ps}^{-1}\ (95\%\ \mathrm{c.l.})$$
$$\to\ |V_{td}| = (8.1 \pm 1.8) \times 10^{-3}\,, \quad |V_{td}/V_{ts}| < 0.217\ (95\%\ \mathrm{c.l.}). \tag{18}$$

Table 7. Direct CP asymmetries of rare hadronic modes.

Mode	Br($\times 10^{-6}$)	$A_{\rm CP}$
$K^{\pm}\pi^{\mp}$	$4.7^{+1.8}_{-1.5} \pm 0.6$	-0.04 ± 0.16
$K^{\pm}\pi^{0}$	$18.8^{+3.0}_{-2.6} \pm 1.3$	-0.29 ± 0.23
$K^{0}\pi^{\pm}$	$12.1^{+3.0\,2.1}_{-2.8\,-1.4}$	$+0.18 \pm 0.24$
$K^{\pm}\eta'$	$18.2^{+4.6}_{-4.0} \pm 1.0$	$+0.03 \pm 0.12$
$\omega\pi^{\pm}$	$11.3^{+3.3}_{-2.9} \pm 1.5$	-0.34 ± 0.25
$\pi^{+}\pi^{-}$	$4.3^{+1.6}_{-1.4} \pm 0.5$	
$K^{0}\pi^{0}$	$14.6^{+5.9\,+2.4}_{-5.1\,-3.3}$	
$\Psi K^{\pm}$		$+0.018 \pm 0.043 \pm 0.004$
$\Psi' K^{\pm}$		$+0.020 \pm 0.091 \pm 0.010$

4.3 *Direct CP asymmetries in hadronic rare B decays*

We have seen CP asymmetry measurements for inclusive and exclusive radiative decays where expected asymmetries are small. Often, rare hadronic decays such as $B \to K\pi$ receives contributions from multiple diagrams (e.g. tree and penguin) with different weak phases. When combined with different final-state strong phases, the rates of $B \to f$ and $\bar{B} \to \bar{f}$ can have a large asymmetry ('direct' CP violation). Sometimes, asymmetries of tens of percents are possible.

Even though these asymmetries depend on the strong phases which are difficult to estimate from the first principles, often more than one modes can be combined to extract relevant weak as well as strong phases [30]. One example is the triangle relation of decay amplitudes for $K^{+}\pi^{0}$, $K^{0}\pi^{+}$, and $\pi^{+}\pi^{0}$ from which the angle γ can be extracted [31]. Recent CLEO results [32] are given in table 6 together with CP asymmetry measurements for $J/\Psi K^{\pm}$ and $\Psi' K^{\pm}$ [33]. All measured asymmetries are consistent with zero at this point. We note, however, that many of the modes used to extract the angle γ have already been observed.

4.4 *Measurement of* $\sin 2\beta$

The time-dependent asymmetry of B^{0} or $\bar{B}^{0}$ to $J/\Psi K_S$ is given by

$$A_{\rm CP}(t) = \sin 2\beta \sin \Delta m t \tag{19}$$

and thus by measuring this quantity, one can extract $\sin 2\beta$. So far, three experiments have reported measurements

$$\sin 2\beta = \begin{cases} 3.2^{+1.8}_{-2.0} \pm 0.5 & \text{(OPAL) [34]} \\ 0.79^{+0.41}_{-0.44} & \text{(CDF) [35]} \\ 0.93^{+0.64}_{-0.88} & \text{(ALEPH) [36].} \end{cases} \tag{20}$$

Even though the errors are still quite large, there is clear indication that $\sin 2\beta$ is positive.

On $\Upsilon(4S)$, one tags one B by lepton or other flavor-specific decay product, and detect the signal $J/\Psi K_S$ for the other B. Here, the $B\bar{B}$ pair is created with a coherent $L = 1$ state and the resulting quantum correlation leads to the time-dependent decay rate given by

$$\Gamma_{\Upsilon 4S \to J/\Psi K_S, \ell^\pm X} = N\mathrm{e}^{-\gamma t_+}(1 \pm \sin 2\beta \sin \delta m t_-) : \quad (21)$$

with $t_\pm = t_1 \pm t_2$ where t_1 is the decay time of $J/\Psi K_S$ and t_2 is the decay time of the tagging side. The time-integrated yield is the same for both flavors of B, and thus, it is not possible to detect the asymmetry unless one measures the time dependence. At CESR, B's are nearly at rest ($\beta_B \sim 0.06$) and it is not possible to perform a competitive measurement of $\sin 2\beta$ using this mode. BaBar and Belle are currently collecting data and it is expected that sum total of about $20\,\mathrm{fb}^{-1}$ will be accumulated by this summer. Such dataset would result in a error in $\sin 2\beta$ of about 0.3. Soon afterward, CDF will begin Run 2 where a substantial increase in sensitivity is expected.

References

[1] I I Bigi, B Blok, M A Shifman and A Vainstein, *Phys. Lett.* **B323**, 408 (1994)
[2] A F Falk, M B Wise and I Dunietz, *Phys. Rev.* **D51**, 1183 (1995)
[3] I Dunietz, J Incandela, F D Snyder and H Yamamoto, *Europhys. J.* **C1**, 211 (1998)
[4] K Wilson, *Phys. Rev.* **179**, 1449 (1969); *Phys. Rev.* **D3**, 1818 (1971)
[5] M Neubert, *Phys. Rep.* **245**, 259 (1994) and references therein
[6] E Bagan, P Ball, V M Braun and P Gosdzinsky, *Nucl. Phys.* **B432**, 3 (1994)
[7] E Bagan, P Ball, V M Braun and P Gosdzinsky, *Phys. Lett.* **B342**, 362 (1995); [Erratum: *Phys. Lett.* **B374**, 363 (1996)]
E Bagan, P Ball, B Fiol and P Gosdzinsky, *Phys. Lett.* **B351**, 546 (1995)
[8] M B Voloshin, *Phys. Rev.* **D51**, 3948 (1995)
[9] CLEO collaboration: B Barish *et al*, *Phys. Rev. Lett.* **76**, 1570 (1996)
[10] Particle Data Group, *Europhys. J.* **C3**, 41 (1998)
[11] The ALEPH collaboration: EPS95 conference reference, eps0404
[12] L3 collaboration: M Acciarri *et al*, *Z. Phys.* **C71**, 379 (1996)
[13] The OPAL collaboration: CERN preprint CERN-EP/99-078 (1999), submitted to *Europhys. J.*
[14] The DELPHI collaboration: Paper submitted to the HEP'99 Conference, Tampere, Finland, DELPHI 99-111 CONF 298 (1999)
[15] CLEO collaboration: T E Coan *et al*, *Phys. Rev. Lett.* **80**, 1150 (1998)
[16] ALEPH collaboration: D Buskulic *et al*, *Phys. Lett.* **B388**, 648 (1996)
[17] OPAL collaboration: G Alexander *et al*, *Z. Phys.* **C72**, 1 (1996)
[18] The DELPHI collaboration, CERN preprint CERN-EP/99-66 (1999), submitted to *Europhys. J.*
[19] CLEO collaboration: J P Alexander *et al*, *Phys. Rev. Lett.* **74**, 3113 (1995); Errata: *Phys. Rev. Lett.* **75**, 4155 (1995)
[20] DELPHI collaboration: P Abreu *et al*, *Phys. Lett.* **B426**, 193 (1998)
[21] CLEO collaboration: M S Alam *et al*, *Phys. Rev. Lett.* **74**, 2885 (1995); CLEO-CONF 99-10, hep-ex/9908022 (1999)
[22] ALEPH collaboration: R Barate *et al*, *Phys. Lett.* **B429**, 169 (1998)
[23] A L Kagan and M Neubert, *Europhys. J.* **C7**, 5 (1999) and references therein
[24] CLEO collaboration: CLEO preprint CLNS 99/1653 (1999)
[25] A Ali, T Ohl and T Mannel, *Phys. Lett.* **B298**, 195 (1993)
[26] S Veseli and M G Olsson, *Phys. Lett.* **B367**, 309 (1996)

[27] CLEO collaboration: CLEO preprint CLNS 99/1611 (1999)
[28] CLEO collaboration: J P Alexander *et al*, *Phys. Rev. Lett.* **77**, 5000 (1996)
[29] Lepton-Photon Symposium, 1999
[30] See for example, R Fleischer, *Indian J. Mod. Phys.* **A12**, 2459 (1997)
[31] M Gronau, J L Rosner and D London, *Phys. Rev.* **D44**, 1454 (1994)
[32] CLEO collaboration: CLEO preprint CLNS 00/1661
[33] CLEO collaboration: CLEO preprint CLNS 99/1651
[34] OPAL collaboration: K Ackerstaff *et al*, *Europhys. J.* **C5**, 379 (1998)
[35] CDF collaboration: *Phys. Rev.* **D61**, 072005 2000
[36] ALEPH collaboration: ALEPH 99-099/CONF 99-054 (1999)