Direct CP Violation in B Decays

M. Gronau
Physics Department, Technion - Israel Insitute of Technology, 32000 Haifa, Israel

We discuss several aspects of direct CP asymmetries in B decays, which are very useful in spite of hadronic uncertainties in asymmetry calculations. 1) Asymmetries in decays to $D^{(*)}K^{(*)}$, $\pi^+\pi^-$, $\rho^+\rho^-$, providing precision tests for the CKM phase γ. 2) Null tests in $B^+ \to J/\psi K^+, \pi^+\pi^0$, where a nonzero asymmetry provides evidence for New Physics. 3) Isospin and broken flavor SU(3) relations among CP asymmetries in $B \to K\pi$, $\pi\pi$ predicting $A_{CP}(B^0 \to K^0\pi^0)$ and $A_{CP}(B^0 \to \pi^0\pi^0)$. 4) The significance of $A_{CP}(B^0 \to K^+\pi^-) \neq A_{CP}(B^+ \to K^+\pi^0)$. 5) A potentially stringent constraint on γ from $A_{CP}(B^+ \to K^+\pi^0)$ and $R_c \equiv 2\Gamma(B^+ \to K^+\pi^0)/\Gamma(B^+ \to K^0\pi^+)$. 6) The role of direct CP asymmetries in $b \to s\bar{q}q$ decays for studying the origin of potential New Physics.

1. Importance of direct CP violation

It took 35 years from the discovery of tiny CP violation in K^0-$\bar{K}^0$ mixing by Christenson, Cronin, Fitch and Turlay [1] to an observation of direct CP violation in $K \to \pi\pi$ by the KTeV [2] and NA48 [3] collaborations. While this observation was very important by itself, ruling out the Superweak hypothesis for CP violation [4], hadronic uncertainties involved in calculating this effect prohibited a precise quantitative test of the CKM framework [5].

Tremendous effort has been devoted by the CLEO collaboration at Cornell, by BaBar at SLAC, Belle at KEK, and by the CDF and D0 collabotaions at Fermilab, to measure direct CP violation in hundreds of charged and neutral B decay modes. A small sample of the measured asymmetries is plotted in Fig. 1 [6]. The asymmetry in $B^0 \to K^+\pi^-$, involving the smallest experimental error, provides unambiguous evidence for direct CP violation.

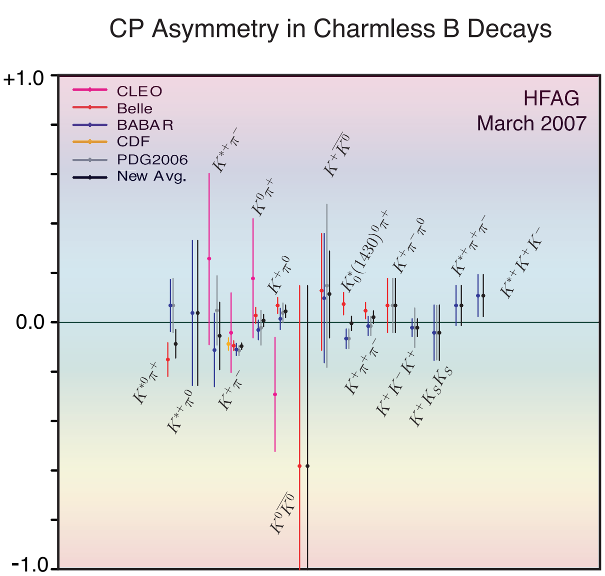

Figure 1: A sample of direct CP asymmetries [6].

1.1. Difficulty of calculating asymmetries

Calculations of direct CP asymmetries involve uncertainties from weak hadronic matrix elements and strong final state phases. To illustrate these uncertainties, consider for instance the decay $B^0 \to K^+\pi^-$ which has a dominant penguin amplitude and a CKM-suppressed tree amplitude, as shown in Fig. 2. The

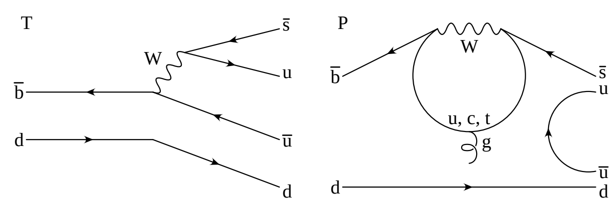

Figure 2: Penguin and tree amplitudes in $B^0 \to K^+\pi^-$.

amplitudes for this decay process and its charge-conjugate are given in terms of suitably defined magnitudes $|P|, |T|$, a CP-conserving strong phase δ, and a CP-violating weak phase $\gamma \equiv \arg(-V^*_{ub}V_{ud}/V^*_{cb}V_{cd})$,

$$A(B^0 \to K^+\pi^-) = |P|e^{i\delta} + |T|e^{i\gamma} \; ,$$
$$A(\overline{B}^0 \to K^-\pi^+) = |P|e^{i\delta} + |T|e^{-i\gamma} \; . \qquad (1)$$

A calculation of the CP asymmetry in terms of γ,

$$A_{CP}(K^+\pi^-) \equiv \frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\overline{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)} = -\frac{2|T/P|\sin\delta\sin\gamma}{1 + |T/P|^2 + 2|T/P|\cos\delta\cos\gamma}, \qquad (2)$$

requires computing $|T/P|$ and δ. This is extremely difficult, as these quantities involve non-perturbative long-distance effects. In QCD calculations based on a heavy quark expansion [7, 8, 9] one faces uncertainties in these quantities from chirally enhanced $1/m_b$-suppressed terms including annihilation contributions from penguin operators, α_s-suppressed terms and "charming penguin" terms [10]. Some of these contributions can be traced back to incalculable soft rescattering amplitudes from $(\bar{s}c)(\bar{c}d)$ intermediate states. A clear distinction between calculable short distance contributions and incalculable soft contributions is particularly challenging for the strong phase δ.

While observing direct CP violation in B decays is important by itself, it then seems that these asymmetries (like the one in $K \to \pi\pi$) cannot provide accurate tests for the mechanism of CP violation, originating in the Standard Model in the phase γ of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. *The purpose of this talk is to show that, in fact, direct asymmetries measured in certain B decay modes do provide precision tests for the CKM framework, in spite of theoretical difficulties in calculating these asymmetries.*

1.2. Determining γ in $B \to D^{(*)}K^{(*)}$

We recall well-known examples of direct CP asymmetries in a whole class of processes $B \to D^{(*)}K^{(*)}$, where D^0 and $\bar{D}^0$ decay to a variety of common final states. These decays provide a clean determination of the weak phase γ [11]. The trick here lies in recognizing the measurements which yield this fundamental CP-violating quantity through interference of tree-level $\bar{b} \to \bar{c}u\bar{s}$ and $\bar{b} \to \bar{u}c\bar{s}$ amplitudes. A broad and up-to-date review of CP violation in the B meson system, including numerous references for studies of $B \to D^{(*)}K^{(*)}$, can be found in Ref. [12].

1.3. Determining γ in $B \to \pi^+\pi^-,\ \rho^+\rho^-$

In $B^0 \to \pi^+\pi^-$ and $B^0 \to \rho^+\rho^-$, mixing-induced asymmetries (S) *and direct asymmetries* ($C \equiv -A_{CP}$) are both needed to fix γ in a rather precise method based on isospin symmetry [13]. Measurements of these asymmetries and conservative assumptions about flavor SU(3) breaking yield the currently most precise value $\gamma = (72 \pm 6)^\circ$ [12, 14, 15], in agreement with $\gamma = (66 \pm 6)^\circ$ obtained from $\Delta m_d/\Delta m_s$ [16].

1.4. Null tests of the CKM framework

Interesting applications of direct CP asymmetries are null tests of the CKM framework in decays where asymmetries are expected to be very small. Two processes dominated by a single CKM phase are $B^+ \to J/\psi K^+$ [17, 18] and $B^+ \to \pi^+\pi^0$, where the Standard Model predicts vanishingly small asymmetries, much smaller than one percent. This includes electroweak penguin contributions in $B^+ \to \pi^+\pi^0$ [19]. A nonzero asymmetry observed in one of these modes at a percent level (as small as it can be with future anticipated precision [6]) would be a clean signature for New Physics.

1.5. Enhanced CP asymmetries

While in general calculating strong phases is very difficult (though phases are known in e.g. $B^+ \to K^+K^-K^+$ mediated by $c\bar{c}$ resonant states [20]), asymmetry measurements provide information for studying the dynamics of hadronic decays. Thus, certain charmless B decays have been predicted to lead to larger asymmetries than others, because they involve two interfering amplitudes with different weak phases, whose ratio is expected to be dynamically enhanced. This may follow from an enhancement of the smaller of the two amplitudes, or a suppression of the larger amplitude. Such effects were noted in an approach using flavor SU(3) symmetry [21, 22], and may probably be realized in QCD calculations [7, 8]. We mention four examples for this enhancement effect using the language of flavor SU(3) amplitudes: (1) $B^+ \to \pi^+\eta$, where an amplitude P smaller than T involves a factor 2, (2) $B^+ \to K^+\eta$, where a potentially dominant P amplitude involves destructive interference between a few quark-level penguin amplitudes [23], (3) $B^+ \to K^+\rho^0$, where subdominant T_V and C_P amplitudes add up constructively, (4) $B^0 \to \rho^\pm\pi^\mp$, which involves constructive interference of P_VT_V and P_PT_P terms.

Table I CP asymmetries involving large $|\Delta S| = 1$ tree-to-penguin ratios or large $\Delta S = 0$ penguin-to-tree ratios [6].

$\pi^+\eta$	$K^+\eta$	$K^+\rho^0$	$\rho^\pm\pi^\mp$
-0.19 ± 0.07	-0.29 ± 0.11	$0.31^{+0.11}_{-0.10}$	-0.13 ± 0.04

Table 1 quotes measured CP asymmetries for these four final states [6]. All four asymmetries are nonzero at a level of about 3σ with central values between 13 and 31 percent. Somewhat higher precision is required in these asymmetry measurements for claiming unambiguous evidence of direct CP violation in these modes.

2. CP asymmetries in $B \to K\pi$

2.1. Isospin sum rules for Γ and A_{CP}

The decays $B^{0,+} \to K\pi$, which occur in four distinct final states, can be expressed in terms of three isospin amplitudes [24]. The initial states are $I(B) = 1/2$, the final states are $I(K\pi) = 1/2, 3/2$ and the effective weak Hamiltonian consists of $\Delta I = 0, 1$. Denoting $\Delta I = 0$ and $\Delta I = 1$ amplitudes by B and A or A', the physical amplitudes for the two pairs of B^+ and B^0 decays are related to each other by isospin reflection, implying [25]

$$A(K^0\pi^+) = B + A,\ \ -A(K^+\pi^-) = B - A, \qquad (3)$$
$$-\sqrt{2}A(K^+\pi^0) = B + A',\ \sqrt{2}A(K^0\pi^0) = B - A'.$$

This leads to an isospin quadrangle relation,

$$A(K^0\pi^+)-A(K^+\pi^-)+\sqrt{2}A(K^+\pi^0)-\sqrt{2}A(K^0\pi^0)=0, \quad (4)$$

which has important physical implications in terms of two approximate sum rules for decay rates Γ [26] and CP rate differences Δ [27]:

$$\begin{aligned}\Gamma(K^+\pi^-)+\Gamma(K^0\pi^+) &\approx 2[\Gamma(K^+\pi^0)+\Gamma(K^0\pi^0)],\\ \Delta(K^+\pi^-)+\Delta(K^0\pi^+) &\approx 2[\Delta(K^+\pi^0)+\Delta(K^0\pi^0)],\end{aligned} \quad (5)$$

where

$$\Delta(K\pi) \equiv \Gamma(\bar{B}\to\bar{K}\bar{\pi}) - \Gamma(B\to K\pi). \quad (6)$$

We now present the shortest proofs for these sum rules, using the dominance of a $\Delta I=0$ penguin amplitude P (part of the isospin amplitude B) in all $B\to K\pi$ decays. Evidence for penguin-dominance is provided by the four measured $B\to K\pi$ decay rates which are equal within 2σ [6],

$$\begin{aligned}R &\equiv \frac{\Gamma(B^0\to K^+\pi^-)}{\Gamma(B^+\to K^0\pi^+)} = 0.90\pm0.05,\\ R_c &\equiv \frac{2\Gamma(B^+\to K^+\pi^0)}{\Gamma(B^+\to K^0\pi^+)} = 1.11\pm0.07,\\ R_n &\equiv \frac{\Gamma(B^0\to K^+\pi^-)}{2\Gamma(B^0\to K^0\pi^0)} = 0.97\pm0.07.\end{aligned} \quad (7)$$

The non-penguin amplitudes are calculated to be much smaller than P, $|\text{non-}P|/|P| \sim 0.1$ [7, 8, 9, 10, 22]. Terms in the two sum rules (5) which are quadratic in P (or B) cancel trivially, while terms which are linear in P cancel because of (4). Thus, the only terms which may violate the two sum rules are quadratic in non-penguin amplitudes, and can be shown to amount to a few percent of each side of the two sum rules (5).

Indeed, the sum rule for decay rates Γ holds within experimental errors which are currently about 5% of each side [6, 28]. The sum rule for CP rate asymmetries Δ, expected to hold within a similar precision, leads to a *prediction for the asymmetry in* $B^0\to K^0\pi^0$ in terms of the other three asymmetries which have been measured with higher precision (see Table II),

$$A_{CP}(B^0\to K^0\pi^0) = -0.140\pm0.043. \quad (8)$$

This prediction, which is expected to hold within a few percent, can be improved by reducing errors in $A_{CP}(K^0\pi^+), A_{CP}(K^+\pi^0)$. While the value (8) is consistent with experiment, higher accuracy in asymmetry measurements is required for testing this prediction following from the rather precise Δ relation (5).

2.2. $A_{CP}(K^+\pi^0)\neq A_{CP}(K^+\pi^-)$ a puzzle?

The measurement of a nonzero CP asymmetry in $B^0\to K^+\pi^-$ provides the first evidence for an interference between a dominant penguin amplitude P and

Table II CP asymmetries in $B\to K\pi$ [6].

$B^0\to K^+\pi^-$	$B^+\to K^+\pi^0$	$B^+\to K^0\pi^+$	$B^0\to K^0\pi^0$
-0.097 ± 0.012	0.047 ± 0.026	0.009 ± 0.025	-0.12 ± 0.11

a small tree amplitude T with a nonzero relative strong phase δ between the two amplitudes. [See Eqs. (1) and (2)]. Such an interference occurs also in $B^+\to K^+\pi^0$, in which a spectator d-quark in $B^0\to K^+\pi^-$ is replaced by a u-quark. No asymmetry has been observed in $B^+\to K^+\pi^0$. An assumption that other contributions to this asymmetry are negligible has raised some questions about the validity of the CKM framework. In fact, a color-suppressed tree amplitude C, also occurring in $B^+\to K^+\pi^0$ [21] (see Fig. 3), resolves this "puzzle" if this amplitude is comparable in magnitude to T. A too naive assumption, $|C|\ll|T|$, has been

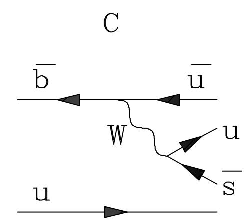

Figure 3: Color-suppressed tree amplitude in $B^+\to K^+\pi^0$

made in Ref. [21] followed by numerous other works.

More recent studies, including a global SU(3) fit for all charmless B decays to two pseudoscalars, have shown that $|C|\sim|T|$ [22, 29, 30]. For consistency between the two CP asymmetries in $B^0\to K^+\pi^-$ and $B^+\to K^+\pi^0$, the strong phase difference between C and T must be negative and cannot be very small [31]. This, and the somewhat large value of C, seem to stand in contrast to QCD calculations using a factorization theorem [7, 9]. While this may be considered a difficulty for QCD calculations, by no means should it be considered evidence for New Physics as argued sometimes.

2.3. A sum rule for $A_{CP}(K^+\pi^0)$ and R_c

The asymmetry $A_{CP}(K^+\pi^0)$ and the ratio of rates R_c defined in (7) involve the decay amplitude for $B^+\to K^+\pi^0$, which seems to confront QCD calculation with a difficulty. The smallness of the measured asymmetry and of the measured value of R_c-1 lead to an interesting constraint on γ which we discuss now.

Including color-favored and color-suppressed electroweak penguin contributions, P_{EW} and P^c_{EW}, one has

$$A(K^+\pi^0) = P + T + C + P_{EW} + P^c_{EW},$$

$$A(K^0\pi^+) = P. \tag{9}$$

A small $1/m_b$-suppressed annihilation amplitude A from a current-current operator has been neglected in the two processes [7, 9, 21, 32]. One introduces two calculable parameters for ratios of amplitudes, $r_c \equiv |T + C|/|P|$ and $\delta_{EW} \equiv |P_{EW} + P^c_{EW}|/|T + C|$. The parameter r_c is given by [33]

$$r_c = \sqrt{2}\frac{V_{us}}{V_{ud}}\frac{f_K}{f_\pi}\sqrt{\frac{\mathcal{B}(B^+ \to \pi^+\pi^0)}{\mathcal{B}(B^+ \to K^0\pi^+)}} = 0.20 \pm 0.02, \tag{10}$$

where the error includes an uncertainty from SU(3) breaking. The parameter δ_{EW} is defined by [34]

$$P_{EW} + P^c_{EW} = -\delta_{EW}e^{-i\gamma}(T + C),$$
$$\delta_{EW} = -\frac{3}{2}\frac{c_9 + c_{10}}{c_1 + c_2}\frac{|V^*_{tb}V_{ts}|}{|V^*_{ub}V_{us}|} = 0.60 \pm 0.05. \tag{11}$$

Here the error is dominated by the current uncertainty in $|V_{ub}|/|V_{cb}|$, including also a smaller error from SU(3) breaking estimated using QCD factorization.

The asymmetry $A_{CP}(K^+\pi^0)$ and the ratio of rates R_c are given, to first order in r_c, by

$$A_{CP}(K^+\pi^0) = -2r_c \sin\gamma \sin\delta_c + \mathcal{O}(r_c^2), \tag{12}$$
$$R_c - 1 = -2r_c(\cos\gamma - \delta_{EW})\cos\delta_c + \mathcal{O}(r_c^2),$$

where δ_c is the strong phase difference between $T + C$ and P. Eliminating δ_c it is now straight forward to prove the following sum rule [31]

$$\left(\frac{A_{CP}(K^+\pi^0)}{\sin\gamma}\right)^2 + \left(\frac{R_c - 1}{\cos\gamma - \delta_{\rm EW}}\right)^2 = (2r_c)^2 + \mathcal{O}(r_c^3). \tag{13}$$

This sum rule implies that at least one of the two terms whose squares occur on the left-hand-side must be sizable, of the order of $2r_c = 0.4$. The first term, $|A_{CP}(B^+ \to K^+\pi^0)|/\sin\gamma$, is already smaller than $\simeq 0.1$, using the current 2σ bounds on γ and $|A_{CP}(B^+ \to K^+\pi^0)|$. Thus, the second term must provide a dominant contribution. For $R_c \simeq 1$, this implies $\gamma \simeq \arccos\delta_{EW} \simeq (53.1 \pm 3.5)^\circ$. This range is expanded by including errors in R_c and $A_{CP}(B^+ \to K^+\pi^0)$. For instance, bounds $0.95 < R_c < 1.1$ would imply an important upper limit, $\gamma < 71^\circ$. Current values of $A_{CP}(K^+\pi^0)$ and R_c lead to an upper limit $\gamma \le 88^\circ$ at 90% confidence level [31]. This bound is consistent with the value of γ obtained from $B \to \pi^+\pi^-$ and $B \to \rho^+\rho^-$, as mentioned above, but is not yet competitive with its precision.

3. SU(3) relations $\Delta(K\pi) = -\Delta(\pi\pi)$

One may prove two useful relations between CP rate differences within the CKM framework [35, 36]:

$$\Delta(K^+\pi^-) = -\Delta(\pi^+\pi^-), \tag{14}$$
$$\Delta(K^0\pi^0) = -\Delta(\pi^0\pi^0). \tag{15}$$

A slightly over-simplified proof of these relations goes as follows. [A precise proof, including electroweak penguin terms and justifying an assumption about negligible $E + PA$ terms can be found in Ref. [12]).] Writing

$$A(K^+\pi^-) = P + T, \tag{16}$$

where P and T contain strong and weak phases, one has in the flavor SU(3) limit

$$A(\pi^+\pi^-) = -\lambda P + \lambda^{-1}T, \tag{17}$$

where $\lambda \equiv V_{us}/V_{ud} = -V_{cd}/V_{cs}$. Similarly,

$$\sqrt{2}A(K^0\pi^0) = P - C,$$
$$\sqrt{2}A(\pi^0\pi^0) = -\lambda P - \lambda^{-1}C. \tag{18}$$

The CP rate differences in the two pairs of processes are given by interference terms between P and T and between P and C, which are equal in magnitude and have opposite signs in $B \to K\pi$ and $B \to \pi\pi$. This proves (14) and (15).

Table III Direct CP asymmetries in $B \to \pi\pi$ [6].

$B^0 \to \pi^+\pi^-$	$B^0 \to \pi^0\pi^0$
0.38 ± 0.07	$0.36^{+0.33}_{-0.31}$

Using branching ratios from [6] and asymmetries in Tables II and III, Eq. (14) reads

$$\mathcal{B}(K^+\pi^-)A_{CP}(K^+\pi^-) = -\mathcal{B}(\pi^+\pi^-)A_{CP}(\pi^+\pi^-),$$
$$(-1.88 \pm 0.24)10^{-6} = (-1.96 \pm 0.37)10^{-6}. \tag{19}$$

Both the signs and the magnitudes agree well, providing evidence for the success of flavor SU(3). We note that using SU(3) breaking factors f_K/f_π for both T and P, as assumed in [35], would imply a factor $(f_K/f_\pi)^2$ on the right-hand-side of (19) leading to a worse agreement. Some reduction of errors in $A_{CP}(K^+\pi^-)$ and $A_{CP}(\pi^+\pi^-)$ is required in order to determine well the pattern of SU(3) breaking in PT.

The relation (15) and the value of $A_{CP}(K^0\pi^0)$ in (8) obtained using isospin symmetry imply a *prediction for* $A_{CP}(\pi^0\pi^0)$,

$$A_{CP}(\pi^0\pi^0) = -A_{CP}(K^0\pi^0)\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(\pi^0\pi^0)} = 1.07 \pm 0.38. \tag{20}$$

The error is dominated by errors in $A_{CP}(K^0\pi^+)$ and $A_{CP}(K^+\pi^0)$. An SU(3) breaking factor f_K/f_π in C would lower this prediction by a factor f_π/f_K. A large positive CP asymmetry in $B^0 \to \pi^0\pi^0$ implies comparable sides in the $\bar{B} \to \pi\pi$ isospin amplitude triangle, but a squashed $B \to \pi\pi$ isospin triangle. This has a simplifying effect on the isospin analysis in $B \to \pi\pi$, where a discrete ambiguity disappears in the limit of a flat $B \to \pi\pi$ triangle [13].

4. CP violation in $b \to s\bar{q}q$

A class of $b \to s\bar{q}q$ penguin-dominated B^0 decays to CP-eigenstates has attracted recently considerable attention. This includes final states XK_S and XK_L, where $X = \phi, \pi^0, \eta', \omega, f_0, \rho^0, K^+K^-, K_SK_S, \pi^0\pi^0$, for which measured mixing-induced asymmetries $\pm S$ (for CP eignstates with eigenvalues $\eta_{CP} = \mp 1$) and *direct asymmetries* $C \equiv -A_{CP}$ are quoted in Table IV [6].

Table IV CP asymmetries in $b \to s\bar{q}q$ for $\eta_{CP} = \mp 1$ [6].

X	ϕ	π^0	η'	ω
$\pm S$	0.39 ± 0.18	0.33 ± 0.21	0.61 ± 0.07	0.48 ± 0.24
C	0.01 ± 0.13	0.12 ± 0.11	-0.09 ± 0.06	-0.21 ± 0.19
X	ρ^0	$f_0(980)$	K^+K^-	K_SK_S
$\pm S$	0.20 ± 0.57	0.42 ± 0.17	$0.58^{+0.18}_{-0.13}$	0.58 ± 0.20
C	0.64 ± 0.46	-0.02 ± 0.13	0.15 ± 0.09	-0.14 ± 0.15

Whereas a value $S = -\eta_{CP} \sin 2\beta = 0.678 \pm 0.025$ [6] is expected approximately [37, 38], the actual average of all corresponding measured entries in Table IV is $\sin \beta_{\rm eff} \equiv \langle -\eta_{CP} S \rangle = 0.53 \pm 0.05$. A question often raised is "*is this* 2.6σ *discrepancy caused by New Physics?*". In a similar manner, one may calculate the *average of all direct CP asymmetries* obtaining a value $\langle A_{CP} \rangle = 0.01 \pm 0.04$, which is small and consistent with zero. *Does this mean that there is very little place for New Physics?*

These two questions, considering averages over several processes, should be considered with care because in the Standard Model both $\Delta S \equiv S + \eta_{CP} \sin 2\beta$ and $C \equiv -A_{CP}$ are process-dependent. The smallness of the asymmetries A_{CP} relative to ΔS may be related to small strong phases δ, because A_{CP} and ΔS are proportional to $\sin \delta$ and $\cos \delta$, respectively [17]. Calculations of these asymmetries involve hadronic uncertainties at a level of several percent, of order λ^2 [39, 40, 41, 42]. It has been pointed out some time ago [43] that if New Physics contributions are at this low level, it becomes difficult to separate them from hadronic uncertainties within the CKM framework.

The importance of *direct CP asymmetries* measured in this class of processes may be demonstrated through two features of C and ΔS, by which one can distinguish New Physics effects from hadronic uncertainties in the Standard Model and learn about the origin of New Physics effects:

- Within the Standard Model C and ΔS can be shown to lie on a circle [17],

$$\left(\frac{\Delta S}{\cos 2\beta}\right)^2 + C^2 = (2\xi \sin \gamma)^2 \,, \qquad (21)$$

  whose radius depends on a process-dependent ratio of tree and penguin amplitudes $\xi \sim \mathcal{O}(\lambda^2)$. The locus on the circle is fixed by a strong phase δ. In most cases one expects $|\delta| < \pi/2$ implying $\Delta S > 0$ [39, 40, 41, 42].

- Once the measured values of C and ΔS disagree with calculations of ξ and the strong phase δ beyond hadronic uncertainties, we will have solid evidence for New Physics. At this point one would seek signatures characterizing classes of models rather than studying effects of specific models of which quite a few exist [38, 44, 45, 46, 47, 48]. A useful way for classifying extensions of the Standard Model is by the isospin behavior, $\Delta I = 0$ or $\Delta I = 1$, of the new effective operators.

Recently it has been shown [25] that the isospin structure of potential New Physics operators contributing to $b \to s\bar{q}q$ can be determined by studying C and ΔS in $B^0 \to XK^0$ together with two other kinds of asymmetries: direct asymmetries A_{CP} in isospin-reflected decays $B^+ \to XK^+$, and isospin-dependent CP-conserving asymmetries defined by

$$A_I \equiv \frac{\Gamma(XK^+) - \Gamma(XK^0)}{\Gamma(XK^+) + \Gamma(XK^0)}. \qquad (22)$$

A study of the currently measured four kinds of asymmetries has shown that potential New Physics contributions to these processes must be small. Some reduction of errors in the measured asymmetries is required for identifying a signature for New Physics and for a useful implementation of this method. We refer the reader to Ref. [25] for details of this analysis.

5. Conclusion

The importance of direct CP violation is demonstrated by using direct asymmetries in $B \to D^{(*)}K^{(*)}, \pi^+\pi^-, \rho^+\rho^-$ for a determination of the weak phase γ. Asymmetries in $B^+ \to J/\psi K^+, \pi^+\pi^0$ provide unambiguous signatures for New Physics. In spite of the difficuly of calculating strong phases, measured asymmetries provide useful information about the dynamics of hadronic decays.

The different asymmetries measured in $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$ cannot be easily explained within QCD calculations, but should not be considered evidence for New Physics. An isospin sum rule among the four $B \to K\pi$ asymmetries predicts $A_{CP}(K^0\pi^0) = -0.140 \pm 0.043$. Small $A_{CP}(K^+\pi^0)$ and small $R_c - 1$ imply an interesting constraint on γ. The flavor SU(3) prediction $A_{CP}(K^+\pi^-)/A_{CP}(\pi^+\pi^-) = -\mathcal{B}(\pi^+\pi^-)/\mathcal{B}(K^+\pi^-)$ works well. The ratio of the two asymmetries fixes the pattern of SU(3) breaking, which is useful for a precise determination of γ. Flavor SU(3) predicts a large positive direct asymmetry in $B \to \pi^0\pi^0$, which has an implication on the $B \to \pi\pi$

isospin analysis. Direct CP asymmetries in $b \to s\bar{q}q$ play a central role in studying New Physics operators, in particular for learning their isospin structure.

Acknowledgments

I would like to thank the Local Organizing Committee for a very interesting and smoothly running conference in a beautiful setting. I am grateful to Jonathan Rosner for a long and fruitful collaboration and to several other short-term collaborators. This work was supported in part by the Israel Science Foundation under Grant No. 1052/04 and by the German-Israeli Foundation under Grant No. I-781-55.14/2003.

References

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch and R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
[2] A. Alavi-Harati *et al.* [KTeV Collaboration], Phys. Rev. Lett. **83**, 22 (1999).
[3] V. Fanti *et al.* [NA48 Collaboration], Phys. Lett. B **465**, 335 (1999).
[4] L. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964).
[5] A. Pich, Nucl. Phys. Proc. Suppl. **93**, 253 (2001).
[6] E. Barberio *et al.* [Heavy Flavor Averaging Group Collaboration], arXiv:0704.3575 [hep-ex], `http://www.slac.stanford.edu/xorg/hfag/`.
[7] M. Beneke, G. Buchalla, M. Neubert and C. T. Sachrajda, Phys. Rev. Lett. **83**, 1914 (1999); Nucl. Phys. B **606**, 245 (2001); M. Beneke and M. Neubert, Nucl. Phys. B **675**, 333 (2003); M. Beneke, G. Buchalla, M. Neubert and C. T. Sachrajda, Phys. Rev. D **72**, 098501 (2005).
[8] Y. Y. Keum, H. n. Li and A. I. Sanda, Phys. Lett. B **504**, 6 (2001); Phys. Rev. D **63**, 054008 (2001); Y. Y. Keum and H. n. Li, Phys. Rev. D **63**, 074006 (2001); H. n. Li, S. Mishima and A. I. Sanda, Phys. Rev. D **72**, 114005 (2005).
[9] C. W. Bauer, D. Pirjol, I. Z. Rothstein and I. W. Stewart, Phys. Rev. D **70**, 054015 (2004); *ibid* **72**, 098502 (2005). See also J. Chay and C. Kim, Phys. Rev. D **68**, 071502 (2003).
[10] M. Ciuchini, E. Franco, G. Martinelli and L. Silvestrini, Nucl. Phys. B **501**, 271 (1997); M. Ciuchini, R. Contino, E. Franco, G. Martinelli and L. Silvestrini, Nucl. Phys. B **512**, 3 (1998); [Erratum-ibid. B **531**, 656 (1998)]; M. Ciuchini, E. Franco, G. Martinelli, M. Pierini and L. Silvestrini, Phys. Lett. B **515**, 33 (2001).
[11] M. Gronau and D. London, Phys. Lett. B **253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991).
[12] M. Gronau, Int. J. Mod. Phys. A **22**, 1953 (2007).
[13] M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990).
[14] M. Beneke, M. Gronau, J. Rohrer and M. Spranger, Phys. Lett. B **638**, 68 (2006).
[15] M. Gronau and J. L. Rosner, arXiv:0704.3459 [hep-ph], to be published in Phys. Lett. B. See also R. Fleischer, S. Recksiegel and F. Schwab, Eur. Phys. J. C **51**, 55 (2007).
[16] J. L. Rosner, arXiv:0704.2774 [hep-ph], summary talk at 42nd Rencontres de Moriond on QCD and Hadronic Interactions, La Thuile, Italy, March 17-24 2007.
[17] M. Gronau, Phys. Rev. Lett. **63**, 1451 (1989).
[18] H. Boos, T. Mannel and J. Reuter, Phys. Rev. D **70**, 036006 (2004); M. Ciuchini, M. Pierini and L. Silvestrini, Phys. Rev. Lett. **95**, 221804 (2005); H. n. Li and S. Mishima, JHEP **0703**, 009 (2007).
[19] A. J. Buras and R. Fleischer, Eur. Phys. J. C **11**, 93 (1999); M. Gronau, D. Pirjol and T. M. Yan, Phys. Rev. D **60**, 034021 (1999).
[20] G. Eilam, M. Gronau and R. R. Mendel, Phys. Rev. Lett. **74**, 4984 (1995); S. Fajfer, T. N. Pham and A. Prapotnik, Phys. Rev. D **70**, 034033 (2004).
[21] M. Gronau, O. F. Hernandez, D. London and J. L. Rosner, Phys. Rev. D **50**, 4529 (1994); *ibid* **52**, 6374 (1995).
[22] C. W. Chiang, M. Gronau, Z. Luo, J. L. Rosner and D. A. Suprun, Phys. Rev. D **69**, 034001 (2004); C. W. Chiang, M. Gronau, J. L. Rosner and D. A. Suprun, Phys. Rev. D **70**, 034020 (2004).
[23] H. J. Lipkin, Phys. Lett. B **254**, 247 (1991).
[24] Y. Nir and H. R. Quinn, Phys. Rev. Lett. **67**, 541 (1991); H. J. Lipkin, Y. Nir, H. R. Quinn and A. Snyder, Phys. Rev. D **44**, 1454 (1991); M. Gronau, Phys. Lett. B **265**, 389 (1991).
[25] M. Gronau and J. L. Rosner, Phys. Rev. D. **75**, 094006 (2007).
[26] M. Gronau and J. L. Rosner, Phys. Rev. D **59**, 113002 (1999); H. J. Lipkin, Phys. Lett. B **445**, 403 (1999).
[27] D. Atwood and A. Soni, Phys. Rev. D **58**, 036005 (1998); M. Gronau, Phys. Lett. B **627**, 82 (2005).
[28] M. Gronau and J. L. Rosner, Phys. Rev. D **74**, 057503 (2006).
[29] A. J. Buras, R. Fleischer, S. Recksiegel and F. Schwab, Phys. Rev. Lett. **92**, 101804 (2004).
[30] S. Baek, P. Hamel, D. London, A. Datta and D. A. Suprun, Phys. Rev. D **71**, 057502 (2005).
[31] M. Gronau and J. L. Rosner, Phys. Lett. B **644**, 237 (2007).
[32] B. Blok, M. Gronau and J. L. Rosner, Phys. Rev. Lett. **78**, 3999 (1997).
[33] M. Gronau, J. L. Rosner and D. London, Phys. Rev. Lett. **73**, 21 (1994).
[34] M. Neubert and J. L. Rosner, Phys. Lett. B **441**, 403 (1998); Phys. Rev. Lett. **81**, 5076 (1998).
[35] N. G. Deshpande and X. G. He, Phys. Rev. Lett. **75**, 1703 (1995); X. G. He, Eur. Phys. J. C **9**, 443

(1999).
[36] M. Gronau and J. L. Rosner, Phys. Rev. Lett. **76**, 1200 (1996); A. S. Dighe, M. Gronau and J. L. Rosner, Phys. Rev. D **54**, 3309 (1996).
[37] D. London and R. D. Peccei, Phys. Lett. B **223**, 257 (1989).
[38] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997).
[39] Y. Grossman, Z. Ligeti, Y. Nir and H. Quinn, Phys. Rev. D **68**, 015004 (2003); M. Gronau and J. L. Rosner, Phys. Lett. B **564**, 90 (2003); C. W. Chiang, M. Gronau and J. L. Rosner, Phys. Rev. D **68**, 074012 (2003); M. Gronau, J. L. Rosner and J. Zupan, Phys. Rev. D **74**, 093003 (2006).
[40] M. Beneke, Phys. Lett. B **620**, 143 (2005).
[41] A. R. Williamson and J. Zupan, Phys. Rev. D **74**, 014003 (2006) [Erratum-ibid. D **74**, 03901 (2006)].
[42] H. Y. Cheng, C. K. Chua and A. Soni, Phys. Rev. D **72**, 014006 (2005); *ibid* **72**, 094003 (2005).
[43] D. Atwood, M. Gronau and A. Soni, Phys. Rev. Lett. **79**, 185 (1997).
[44] M. Gronau and D. London, Phys. Rev. D **55**, 2845 (1997).
[45] M. Ciuchini, E. Franco, G. Martinelli, A. Masiero and L. Silvestrini, Phys. Rev. Lett. **79**, 978 (1997).
[46] G. Hiller, Phys. Rev. D **66**, 071502 (2002).
[47] N. G. Deshpande and D. K. Ghosh, Phys. Lett. B **593**, 135 (2004).
[48] V. Barger, C. W. Chiang, P. Langacker and H. S. Lee, Phys. Lett. B **580**, 186 (2004); *ibid* **598**, 218 (2004).