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CP VIOLATION IN *B* DECAY – STANDARD MODEL PREDICTIONS

Revised February 1998 by H. Quinn (SLAC).

The study of CP violation in B decays [1] offers an opportunity to test whether the Standard Model mechanism for CP violation, due to the phase structure of the CKM matrix, is the only source of such effects [2]. The known CP-violation effects in K decays can be accommodated by this mechanism, but do not provide a critical test of it.

The Unitarity conditions (see our Section on "The Cabibbo-Kobayashi-Maskawa mixing matrix")

$$V_{uq}V_{ub}^* + V_{cq}V_{cb}^* + V_{tq}V_{tb}^* = 0 \ , \tag{1}$$

with $q = s$ or $q = d$ where V_{ij} is an element of the CKM matrix can be represented as triangles in the complex plane. The three interior angles of the $q = d$ triangle are labeled

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \ , \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \ ,$$
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \ . \tag{2}$$

In terms of the Wolfenstein parameters [3] we can also write

$$\tan\alpha = \frac{\eta}{\eta^2 - \rho(1-\rho)} \ , \quad \tan\beta = \frac{\eta}{1-\rho} \ ,$$
$$\tan\gamma = \frac{\eta}{\rho} \ . \tag{3}$$

Notice that the sign as well the magnitude of these angles is meaningful and can be measured.

A major aim of CP-violation studies of B decays is to make enough independent measurements of the sides and angles that the Unitarity triangle is overdetermined and thereby to check the validity of the Standard Model predictions that relate various measurements to aspects of this triangle. Constraints can be made on the basis of present data on the B-meson masses and lifetimes, on the ratio of charmless decays to decays with charm (V_{ub}/V_{cb}), and on ϵ [4] in K decays. These constraints have been discussed in many places in the literature; for a recent summary see Ref. 5. The range of allowed values depends on matrix element estimates, these are difficult to calculate hadronic physics effects. Improved methods to calculate such quantities, and understand the uncertainties in them, are needed to further sharpen tests of the Standard Model. Because of the uncertainties in these quantities, any given "Standard Model allowed range," for example for (ρ, η), cannot be interpreted as a statistically-based error range.

The phases in decay amplitudes which arise because of the phase in the CKM matrix, are called weak phases; the phases which arise from final state rescattering effects are referred to as strong phases. When one compares the amplitude for decay to a CP eigenstate to that for the related CP-conjugate process, the weak phase ϕ_i of each contribution changes sign, while the strong phase δ_i is unchanged:

$$\mathcal{A} = \Sigma_i \mathcal{A}_i e^{i(\delta_i+\phi_i)} \ , \ \overline{\mathcal{A}} = \Sigma_i \mathcal{A}_i e^{i(\delta_i-\phi_i)} \ . \tag{4}$$

Direct CP violation is a difference in the direct decay rate between $B \to f$ and $\overline{B} \to \overline{f}$ without any contribution from mixing effects. This requires $|\mathcal{A}| \neq |\overline{\mathcal{A}}|$, which occurs only if there is more than one term in the sum Eq. (4), and then only if the two terms have both different weak phases and different strong phases. A nonzero result for $\mathrm{Re}(\epsilon'/\epsilon)$ in K decay is a direct CP-violation effect. Direct CP violation can occur both in charged channels and in neutral channels in B decays [4].

In the Standard Model direct CP violation occurs because there are two major classes of diagrams that contribute to weak decays, tree diagrams, and penguin diagrams, examples of which are shown in Fig. 1. Tree diagrams are those in which the W does not reconnect to the quark line from which it was emitted. Penguin diagrams are loop diagrams in which the W is re absorbed on the same quark line, producing a net change of flavor, and a gluon (for a strong penguin) or a photon or Z (for an electroweak penguin) is emitted from the loop. There may be several different tree diagrams for a given process, namely W emission and decay, W decay, W exchange between the initial valence quarks, and/or valence quark-antiquark annihilation to produce the W. However all such contributions which enter a given transition do so with the same CKM (weak) phase. Direct CP violation occurs because of interference between tree diagrams and those penguin diagrams which have different weak phases than the trees. In channels where there are no tree contributions, direct CP violation can arise because of interference between different penguin contributions.

To calculate the size of expected CP-violation effects one begins from the relevant quark decay diagrams. We divide the amplitudes into two factors: a CKM factor given by the CKM-matrix elements that enter at each W vertex, and a Feynman amplitude from evaluating the remainder of the diagram. The Feynman amplitude of the penguin diagram is suppressed relative to tree diagrams by a factor of order $\alpha_s(m_b)/4\pi$. Firm predictions based on this argument for the strength of the CP-violating effects in particular exclusive charged B-decay channels are not possible because the relationship between

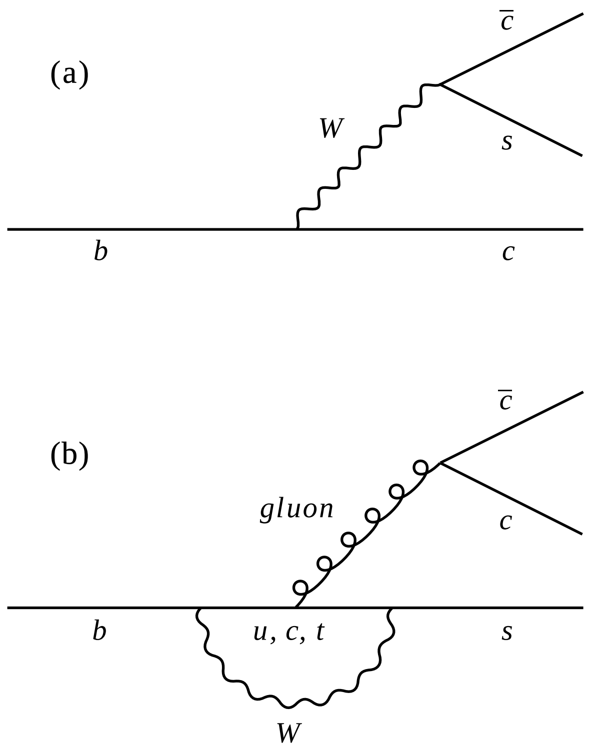

Figure 1: Quark level processes for $b \to c\overline{c}s$: (a) Tree diagram; (b) Penguin diagram. In the case of electroweak penguin contributions, the *gluon* is replaced by a Z or a γ.

the free-quark decay diagrams and the exclusive meson-decay amplitudes depends on operator matrix elements and thus estimates are model dependent. Furthermore one cannot reliably predict the strong phases that contribute to the asymmetry.

There is one interesting exception to this last statement that gives a possible way to find large direct CP-violation effects with known strong phase differences. This is any situation where two or more resonance channels contribute to the same final state set of particles in overlapping kinematic regions. The dominant contributions to the strong phases are then the resonant decay phases, which are known from measurements that determine the resonance mass and width. These give a known strong phase contribution which varies with the kinematics of the final particles and overlays the fixed strong phase of the resonance-production process. If two such resonant channels interfere, then there is a large and kinematically-varying known contribution to the strong phase difference between the contributions of the two channels. Examples include the interference of the different ρ-π charge combinations in the three pion final states [6] or interference between different $K^*\pi$ combinations in $K\pi\pi$ states. Detailed exploration of possible applications of these ideas can be found in Ref. 7.

A second type of CP violation, referred to as indirect CP violation, or CP violation in the mixing, would arise from any difference in the widths $\Delta\Gamma$ of the two mass eigenstates, or more precisely from complex mixing effects $\mathrm{Arg}(\Gamma_{12}M_{12}^*) \neq 0$, that would give $|q/p| \neq 1$ and also give a nonvanishing lifetime difference for the two B mass eigenstates [8]. Indirect CP violation in the K system is responsible for Re $\epsilon \neq 0$, which give CP-violating asymmetries in leptonic decay rates. Such effects are expected to be tiny in the B_d system, where both $|q/p|-1$ and the difference of lifetimes $\Delta\Gamma/\Gamma$ are expected to be of order 10^{-2} [8]. For B_s a difference in the widths is possible, due to the fact that a number of the simplest two-body channels contribute only to a single CP. The difference in widths could be as much as 20% of the total width in the B_s system [9]. However the quantity $|q/p| - 1$ is expected to be even smaller in the B_s system than in the B_d system. An indirect CP-violating asymmetry would be seen as an charge asymmetry in the same-sign dilepton events produced via mixing from an incoherent state that initially contains a $B^0\overline{B}^0$ pair. This asymmetry vanishes with $\Delta\Gamma$; it is expected to be no larger than 1% in B_d decays [10].

There are additional CP-violating effects in neutral B decays which arise from interference between the two paths to a given final state f

$$B \rightarrow f \text{ or } B \rightarrow \overline{B} \rightarrow f \tag{5}$$

This effect, an interference between decay with and without mixing, is seen also in K decays where it contributes to the parameter Im ϵ. This interference can produce rate differences between B decay to a CP-eigenstate and the CP-conjugate $\overline{B}$ decay. Such asymmetries can be directly related to the CKM phases, provided there is no direct CP violation in addition to this effect. In channels where there is also direct CP violation, the relationship between the measured asymmetry and the CKM parameters is more complicated.

A simple way to distinguish the three types of CP violation is to note that direct CP violation occurs when $|\overline{\mathcal{A}}/\mathcal{A}| \neq 1$ while indirect CP violation requires $|q/p| \neq 1$ (see the review on B^0–$\overline{B}^0$ Mixing). CP violation due to the interference between direct decay and decay after mixing can occur when both quantities have unit absolute value; it requires only that their product have a nonzero weak phase [11].

Neutral B decays to CP eigenstates: The decays of neutral B mesons into CP eigenstates are of particular interest because many of these decays allow clean theoretical interpretation in terms of the parameters of the Standard Model [12]. We denote such a state by f_{CP}, for example $f_{CP} = J/\psi(1S)K_S$ or $f_{CP} = \pi\pi$, and define the amplitudes

$$\mathcal{A}_{f_{CP}} \equiv \left\langle f_{CP} | B^0 \right\rangle , \quad \overline{\mathcal{A}}_{f_{CP}} \equiv \left\langle f_{CP} | \overline{B}^0 \right\rangle \ . \tag{6}$$

For convenience let us introduce the quantity $\lambda_{f_{CP}}$

$$\lambda_{f_{CP}} \equiv \frac{q}{p}\,\frac{\overline{\mathcal{A}_{f_{CP}}}}{\mathcal{A}_{f_{CP}}}\ . \tag{7}$$

In the limit of no CP violation, $\lambda_{f_{CP}} = \pm 1$, where the sign is given by the CP eigenvalue of the particular state f_{CP}.

When the small difference in width of the two B_d states is ignored we can write

$$(q/p)_{B_d} = \frac{(V_{tb}^* V_{td})}{(V_{tb} V_{td}^*)} = e^{-2i\phi_M}\ , \tag{8}$$

where $2\phi_M$ denotes the CKM phase of the B–$\overline{B}$ mixing diagram (see the review on B^0–$\overline{B}^0$ Mixing). The time-dependent decay width for an initial $B^0(\overline{B}^0)$ state to decay to a state f is then given by

$$\begin{aligned}
&\Gamma(B^0_{\rm phys}(t) \to f_{CP}) = \\
&\quad |\mathcal{A}_{f_{CP}}|^2 e^{-\Gamma t}\Big[\frac{1+|\lambda_{f_{CP}}|^2}{2} + \frac{1-|\lambda_{f_{CP}}|^2}{2} \\
&\qquad \times \cos(\Delta M t) - {\rm Im}\,\lambda_{f_{CP}} \sin(\Delta M t)\Big], \\
&\Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP}) = \\
&\quad |\mathcal{A}_{f_{CP}}|^2 e^{-\Gamma t}\Big[\frac{1+|\lambda_{f_{CP}}|^2}{2} - \frac{1-|\lambda_{f_{CP}}|^2}{2} \\
&\qquad \times \cos(\Delta M t) + {\rm Im}\,\lambda_{f_{CP}} \sin(\Delta M t)\Big]\ .
\end{aligned} \tag{9}$$

The time-dependent CP asymmetry is thus

$$\begin{aligned}
a_{f_{CP}}(t) &\equiv \frac{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) - \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})}{\Gamma(B^0_{\rm phys}(t) \to f_{CP}) + \Gamma(\overline{B}^0_{\rm phys}(t) \to f_{CP})} \\
&= \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta M t) - 2{\rm Im}\,(\lambda_{f_{CP}})\sin(\Delta M t)}{1+|\lambda_{f_{CP}}|^2}\ .
\end{aligned} \tag{10}$$

Further, when there is no direct CP violation in a channel, that is when all amplitudes that contribute have the same CKM decay-phase, ϕ_D, then $|\mathcal{A}_{f_{CP}}/\overline{\mathcal{A}_{f_{CP}}}| = 1$. In that case $\lambda_{f_{CP}}$ depends on CKM-matrix parameters only, without hadronic uncertainties, and can be written $\lambda_{f_{CP}} = \pm e^{-2i(\phi_D+\phi_M)}$. Then Eq. (10) simplifies to

$$\begin{aligned} a_{f_{CP}}(t) &= -\mathrm{Im}\,(\lambda_{f_{CP}})\sin(\Delta M t) \\ &= \pm\sin(2(\phi_M+\phi_D))\sin(\Delta M t)\ . \end{aligned} \tag{11}$$

where the overall sign is given by the CP eigenvalue, ±1, of the final state f_{CP}. The mixing phase ϕ_M and the decay phase ϕ_D are each convention dependent, that is their value can be changed by redefining the phases of some of the quark fields. However Im $\lambda_{f_{CP}}$ depends on convention-independent combinations of CKM parameters only. From Eq. (11) one can directly relate the measured CP-violating asymmetry to the phase of particular combination of CKM-matrix elements in the Standard Model.

Extracting CKM parameters from measured asymmetries: In order make this relationship one looks at the CKM elements that appear in the relevant decay amplitudes and in the mixing diagrams. If the final state of the decay includes a K_S, an additional contribution from the K-mixing phase must be included in relating the measured asymmetry to the CKM parameters.

Whenever a penguin amplitude can contribute there are three separate diagrams, corresponding to the three flavors of up-type quarks in the loop. Each of these has a different CKM coefficient. We use the Unitarity condition Eq. (1) to express one coefficient as minus the sum of the other two. This regroups

Table 1: $B \to q\overline{q}s$ decay modes

Quark process	Leading term	Secondary term	Sample B_d modes	B_d angle	Sample B_s modes	B_s angle
$b \to c\overline{c}s$	$V_{cb}V^*_{cs} = A\lambda^2$ tree + penguin$(c-t)$	$V_{ub}V^*_{us} = A\lambda^4(\rho - i\eta)$ penguin only$(u-t)$	$J/\psi\ K_S$	β	$\psi\eta$ $D_s\overline{D}_s$	0
$b \to s\overline{s}s$	$V_{cb}V^*_{cs} = A\lambda^2$ penguin only$(c-t)$	$V_{ub}V^*_{us} = A\lambda^4(\rho - i\eta)$ penguin only$(u-t)$	ϕK_S	β	$\phi\eta'$	0
$b \to u\overline{u}s$ $b \to d\overline{d}s$	$V_{cb}V^*_{cs} = A\lambda^2$ penguin only$(c-t)$	$V_{ub}V^*_{us} = A\lambda^4(\rho - i\eta)$ tree + penguin$(u-t)$	$\pi^0\ K_S$ ρK_S	competing terms	$\phi\pi^0$ $K_S\overline{K}_S$	competing terms

the three terms as a sum of two terms each of which involves a difference of two penguin diagrams (and thus is an ultra-violet finite quantity). As we will see below, the most convenient regrouping is different for $b \to q\overline{q}s$ decays and for $b \to q\overline{q}d$ decays.

When there is a tree diagram one of the two penguin terms will have the same CKM coefficient (and hence the same weak phase) as the tree diagram. Terms with the same weak phase can always be treated as a single contribution, from the perspective of looking for CP violations, although one must be sure to include all the relevant operators when estimating the expected size of such a term. In what follows we use the term “tree-dominated contribution” to describe a tree contribution plus any penguin contribution with the same weak phase. We label the second penguin term, which has a different CKM coefficient from the tree diagram as a “pure penguin contribution.” Where no tree diagrams contribute there are two pure penguin terms. With this convention there are at most two terms with different weak decay phases that contribute for any decay in the Standard Model. It is instructive to note that any beyond-Standard-Model contribution, whatever its weak phase, can always be written as a sum of two terms with the weak phases of the two Standard Model terms, thus it is the pattern of relative strengths, and isospin structure, of the two terms that is peculiar to the Standard Model. (Care should be taken when comparing the terms defined by this grouping with statements in the literature about the sizes of terms made using definitions that do not include this regrouping.)

Table 1 gives the CKM factors for the various $b \rightarrow q\overline{q}'s$-quark decay channels. Here we choose to group penguin terms by eliminating the coefficient $V_{ts}V_{tb}^*$. Note that the two penguin terms in this arrangement are each the difference between a top quark contribution and a lighter (c or u) quark contribution, so they differ only by the mass dependent factors in this second contribution and by their overall sign and the CKM factors. One is suppressed by the CKM factor $\lambda^2(\rho - i\eta)$ compared to the other.

The columns labeled "Sample B_d Modes" and "Sample B_s Modes" list some of the simplest CP-study modes for each case. (These are either CP eigenstates, or modes from which CP-eigenstate contributions can be isolated, for example by angular analysis.) The columns labeled"Angle" show the angle of the unitarity triangle measured by $\phi_M + \phi_D$ where ϕ_M is the weak phase due to mixing, and ϕ_D that of the dominant decay amplitude (only the sum of these quantities is convention independent). Any Cabibbo-suppressed pure-penguin terms gives a negligible correction to this result. For the decay $b \rightarrow s\overline{s}s$ there is no tree contribution so the angle given is that due to the dominant penguin term, ignoring the Cabibbo-suppressed penguin term.

The quark decays to $u\overline{u}s$ and $d\overline{d}s$ contribute to the same set of final state hadrons and so must be combined. Here the tree diagram contributes to the Cabibbo-suppressed amplitude, so that the net result is that the two terms are expected to give comparable contributions with different CKM phases. For these decays, as with other direct CP-violating processes, there is no simple relationship between the measured asymmetry and a CKM phase, and thus no entry in the "Angle" columns in Table 1.

In addition to the neutral CP-eigenstate methods to determine the angles of the unitarity triangle listed in the tables, there are a number of other methods that involve decays that self-tag B-flavor, such as $DK^*(892)$ in either neutral [13] or charged [14] B decays. Further methods to measure γ in charged $B \to DK$ or $B \to D\pi$ have been suggested [15], which use interferences between a suppressed B decay followed by an allowed D decay and an allowed B decay followed by a suppressed D decay. However the relationship between the decay asymmetry and the angle is not as simple as Eq. (11) in this case. These methods require accurate measurements of several branching ratios, including a number that are quite small.

In Table 2 we list decays $b \to q\overline{q}'d$ decays. Here we choose to eliminate whichever of the two terms $V_{ud}V^*_{ub}$ or $V_{cd}V^*_{cb}$ is not present in the tree diagrams, so that the two penguin terms are one with the same weak phase as the tree and a second with CKM coefficient $V_{td}V^*_{tb}$ which has the opposite weak phase as the dominant mixing term in the Standard Model and hence a known value, zero, for $\phi_M + \phi_D$.

Here the competition between the tree-dominated and pure-penguin amplitudes is stronger because there is no Cabibbo suppression of the latter. The pure-penguin contributions are

Table 2: $B \to q\overline{q}d$ decay modes

Quark process	Leading term	Secondary term	Sample B_d modes	B_d angle	Sample B_s modes	B_s angle
$b \to c\overline{c}d$	$V_{cb}V^*_{cd} = -A\lambda^3$ tree + penguin$(c-u)$	$V_{tb}V^*_{td} = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-u)$	D^+D^-	$^*\beta$	ψK_S	$^*\beta_s$
$b \to s\overline{s}d$	$V_{tb}V^*_{td} = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-u)$	$V_{cb}V^*_{cd} = A\lambda^3$ penguin only$(c-u)$	$\phi\pi$ $K_S\overline{K}_S$	competing terms	ϕK_S	competing terms
$b \to u\overline{u}d$ $b \to d\overline{d}d$	$V_{ub}V^*_{ud} = A\lambda^3(\rho-i\eta)$ tree + penguin$(u-c)$	$V_{tb}V^*_{td} = A\lambda^3(1-\rho+i\eta)$ penguin only$(t-c)$	$\pi\pi$; $\pi\rho$ $\pi\, a_1$	$^*\alpha$	π^0K_S ρ^0K_S	competing terms
$b \to c\overline{u}d$	$V_{cb}V^*_{ud} = A\lambda^2$	0	$D^0\pi^0$, $D^0\rho^0$	β	D^0K_S	0
			↳ CP eigenstate		↳ CP eigenstate	

*Leading terms only.

expected to be somewhat smaller because of the $\alpha(m_b)/\pi$ suppression factor. Table 2 lists the angle $\phi_M + \phi_D$, using ϕ_D for the tree-dominated terms as the angle measured. However the measured angle may be significantly shifted from this value if the pure-penguin terms turn out to be large. In certain cases one still may be able to extract a measurement of an angle, for example of $\sin(2\alpha)$ from the $\pi^+\pi^-$ asymmetry by measuring the rates in several isospin-related channels and using a multiparameter fit to separate a tree-only contribution [16]. The impact of electroweak penguins, which will not be removed by this analysis [17] is quite small in this channel [18]. This isospin analysis requires measuring the decay rate for channel $\pi^0\pi^0$, which will be a challenge. For the $\rho\pi$ decays the restrictions due to isospin can again be used to make a multiparameter fit to the ρ-regions of the Dalitz plot for $\pi^+\pi^-\pi^0$ distribution [6]. The interference between different ρ-charge channels is significant and may provide sufficient information to allow the separation of tree-dominated and pure-penguin effects and thus extraction of the parameter α. Isospin analyses at the very least can be used to test whether the penguin contributions are indeed small enough to be neglected in the determination of α.

In the case $b \to s\overline{s}d$ there are no tree graph contributions. The phase of the dominant penguin contribution is such that, combined with mixing effects, it gives a zero asymmetry for B_d decays and an asymmetry proportional to β for B_s decays. However, Gérard and Hou [19] have pointed out that interference with the sub-dominant penguin terms, proportional to $V_{ub}V^*_{ud}$ can give significant direct CP-violation asymmetries for such channels. Fleischer [20] has estimated that this asymmetry is possibly as large as 50%. While the sub-dominant term in this case would vanish if the masses of the up quark and the charm quark were equal, these estimates, which are based on the actual quark mass values and extreme values of operator matrix elements estimated using models, cannot be excluded. Thus, contrary to some comments in the literature, observation of CP-violating asymmetries in channels such as $B_d \to \phi\pi^0$ or $K^0\overline{K}^0$ would not necessarily require beyond-Standard-Model effects to explain them.

The entry for $b \to c\overline{u}d$ where the D^0 decays to a CP eigenstate ignores the small effect of doubly-Cabibbo-suppressed D-decays [21]. In contrast, the last entry indicates that one can select modes reached only by doubly-Cabibbo-suppressed decays from $D^0\pi$ and observe their interference with unsuppressed decays to the same channel from $\overline{D}^0\pi$ states, and thereby obtain a measurement of gamma [22].

There are some decay channels which are common to the B^0 and $\overline{B}^0$ but which are not CP eigenstates. For example the channel $J/\psi(1S)K^*(892)$ where the $K^*(892) \to K_S\pi^0$, the final state is not a CP eigenstate because both even and odd relative angular momenta between the $J/\psi(1S)$ and the $K^*(892)$ are allowed. One can use angular analysis to separate the different CP final states and measure the asymmetry in each [23]. The method applies in many quasi-two-body decays, such as other vector-vector channels, or those with higher-spin particles in final states. The branching ratio to these channels may be significantly larger than the CP-eigenstate (vector-scalar or scalar-scalar) channels with the same quark content. Such angular analyses may therefore be important in achieving accurate values for the parameters α and β.

Additional ways to extract CKM parameters by relationships between rates for channels such as $\pi\pi$, πK that can be extracted using SU(3) invariance have received considerable attention in the literature [24]. While these relationships will be interesting to investigate, the uncertainties introduced by SU(3) corrections may be significant. The review by Buras [5] gives a good summary of these ideas.

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CP VIOLATION PARAMETERS

$|\mathrm{Re}(\epsilon_{B^0})|$

CP Impurity in B^0_d system. It is obtained from $a_{\ell\ell}$, the charge asymmetry in like-sign dilepton events at the $\Upsilon(4S)$.

$$\mathrm{Re}(\epsilon_{B^0}) \simeq \frac{1}{4} a_{\ell\ell} = \frac{1}{4}\,\frac{N(\ell^+\ell^+)-N(\ell^-\ell^-)}{N(\ell^+\ell^+)+N(\ell^-\ell^-)} \ .$$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.002±0.007±0.003	[315] ACKERSTAFF	97U	OPAL	$e^+e^- \rightarrow Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.045	[316] BARTELT	93	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

[315] ACKERSTAFF 97U assumes *CPT* and is based on measuring the charge asymmetry in a sample of B^0 decays defined by lepton and Q_{hem} tags. If *CPT* is not invoked, $\mathrm{Re}(\epsilon_B) = -0.006 \pm 0.010 \pm 0.006$ is found. The indirect *CPT* violation parameter is determined to $\mathrm{Im}(\delta B) = -0.020 \pm 0.016 \pm 0.006$.

[316] BARTELT 93 finds $a_{\ell\ell} = 0.031 \pm 0.096 \pm 0.032$ which corresponds to $|a_{\ell\ell}| < 0.18$, which yields the above $\mathrm{Re}(\epsilon_{B^0})$.

$B^0 \rightarrow D^{*-}\ell^+\nu_\ell$ FORM FACTORS

See the review "Semileptonic decays of *B* mesons" for the definition of these parameters.

R_1 (form factor ratio $\sim V/A_1$)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.18±0.30±0.12	DUBOSCQ	96	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

R_2 (form factor ratio $\sim A_2/A_1$)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.71±0.22±0.07	DUBOSCQ	96	CLE2	$e^+e^- \rightarrow \Upsilon(4S)$

$\rho^2_{A_1}$ (form factor slope)

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.91±0.15±0.06	DUBOSCQ	96	CLE2	$e^+ e^- \rightarrow \Upsilon(4S)$

B^0 REFERENCES

ABBOTT	98B	PL B423 419	B. Abbott+	(D0 Collab.)
ABE	98	PR D57 R3811	F. Abe+	(CDF Collab.)
ABE	98B	PR D57 5382	F. Abe+	(CDF Collab.)
ABE	98C	PRL 80 2057	F. Abe+	(CDF Collab.)
ACCIARRI	98D	EPJ C (to be publ.)	M. Acciarri+	(L3 Collab.)
CERN-EP/98-28				
BEHRENS	98	PRL 80 3710	B.H. Behrens+	(CLEO Collab.)
BRANDENB...	98	PRL 80 2762	G. Brandenbrug+	(CLEO Collab.)
GODANG	98	PRL 80 3456	R. Godang+	(CLEO Collab.)
NEMATI	98	PR D57 5363	B. Nemati+	(CLEO Collab.)
ABE	97J	PRL 79 590	+Abe, Akagi, Allen+	(SLD Collab.)
ABREU	97F	ZPHY C74 19	+Adam, Adye, Agasi+	(DELPHI Collab.)
Also	97K	ZPHY C75 579 erratum		
ABREU	97N	ZPHY C76 579	P. Abreu+	(DELPHI Collab.)
ACCIARRI	97B	PL B391 474	M. Acciarri+	(L3 Collab.)
ACCIARRI	97C	PL B391 481	M. Acciarri+	(L3 Collab.)
ACKERSTAFF	97G	PL B395 128	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97U	ZPHY C76 401	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	97V	ZPHY C76 417	K. Ackerstaff+	(OPAL Collab.)
ARTUSO	97	PL B399 321	M. Artuso+	(CLEO Collab.)
ASNER	97	PRL 79 799	D. Asner+	(CLEO Collab.)
ATHANAS	97	PRL 79 2208	M. Athanas+	(CLEO Collab.)
BUSKULIC	97	PL B395 373	D. Buskulic+	(ALEPH Collab.)
BUSKULIC	97D	ZPHY C75 397	D. Buskulic+	(ALEPH Collab.)
FU	97	PRL 79 3125	X. Fu+	(CLEO Collab.)
JESSOP	97	PRL 79 4533	C.P. Jessop+	(CLEO Collab.)
ABE	96B	PR D53 3496	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ABE	96C	PRL 76 4462	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96H	PRL 76 2015	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ABE	96L	PRL 76 4675	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96Q	PR D54 6596	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABREU	96P	ZPHY C71 539	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	96Q	ZPHY C72 17	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	96E	PL B383 487	+Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ADAM	96D	ZPHY C72 207	W. Adam+	(DELPHI Collab.)
ALBRECHT	96D	PL B374 256	+Hamacher, Hofmann, Kirchhoff+	(ARGUS Collab.)
ALEXANDER	96T	PRL 77 5000	+Bebek, Berger, Berkelman+	(CLEO Collab.)
ALEXANDER	96V	ZPHY C72 377	G. Alexander+	(OPAL Collab.)
ASNER	96	PR D53 1039	+Athanas, Bliss, Brower+	(CLEO Collab.)
BARISH	96B	PRL 76 1570	+Chadha, Chan, Eigen+	(CLEO Collab.)
BISHAI	96	PL B369 186	+Fast, Gerndt, Hinson+	(CLEO Collab.)
BUSKULIC	96J	ZPHY C71 31	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	96V	PL B384 471	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
DUBOSCQ	96	PRL 76 3898	+Fulton, Fujino, Gan+	(CLEO Collab.)
GIBAUT	96	PR D53 4734	+Kinoshita, Pomianowski, Barish+	(CLEO Collab.)
PDG	96	PR D54 1		
ABE	95Z	PRL 75 3068	+Albrow, Amendolia, Amidei+	(CDF Collab.)
ABREU	95N	PL B357 255	+Adam, Adye, Agasi+	(DELPHI Collab.)
ABREU	95Q	ZPHY C68 13	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	95H	PL B363 127	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ACCIARRI	95I	PL B363 137	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ADAM	95	ZPHY C68 363	+Adye, Agasi, Ajinenko+	(DELPHI Collab.)
AKERS	95J	ZPHY C66 555	+Alexander, Allison, Ametewee+	(OPAL Collab.)
AKERS	95T	ZPHY C67 379	+Alexander, Allison, Ametewee+	(OPAL Collab.)
ALEXANDER	95	PL B341 435	+Bebek, Berkelman, Bloom+	(CLEO Collab.)
Also	95C	PL B347 469 (erratum)	Alexander, Bebek, Berkelman, Bloom+	(CLEO Collab.)
BARISH	95	PR D51 1014	+Chadha, Chan, Cowen+	(CLEO Collab.)
BUSKULIC	95N	PL B359 236	+Casper, De Bonis, Decamp+	(ALEPH Collab.)
ABE	94D	PRL 72 3456	+Albrow, Amidei, Anway-Wiese, Apollinari	(CDF Collab.)
ABREU	94M	PL B338 409	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
AKERS	94C	PL B327 411	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	94H	PL B336 585	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)

AKERS	94J	PL B337 196	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	94L	PL B337 393	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
ALAM	94	PR D50 43	+Kim, Nemati, O'Neill, Severini+	(CLEO Collab.)
ALBRECHT	94	PL B324 249	+Ehrlichmann, Hamacher+	(ARGUS Collab.)
ALBRECHT	94G	PL B340 217	+Hamacher, Hofmann, Kirchhoff, Mankel+	(ARGUS Collab.)
AMMAR	94	PR D49 5701	+Ball, Baringer, Bean, Besson, Coppage+	(CLEO Collab.)
ATHANAS	94	PRL 73 3503	+Brower, Masek, Paar, Gronberg+	(CLEO Collab.)
Also	95	PRL 74 3090 (erratum)	Athanas, Brower, Masek, Paar+	(CLEO Collab.)
BUSKULIC	94B	PL B322 441	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
PDG	94	PR D50 1173	Montanet+	(CERN, LBL, BOST, IFIC+)
PROCARIO	94	PRL 73 1306	+Balest, Cho, Daoudi, Ford+	(CLEO Collab.)
STONE	94	HEPSY 93-11		
ABREU	93D	ZPHY C57 181	+Adam, Adye, Agasi, Alekseev+	(DELPHI Collab.)
ABREU	93G	PL B312 253	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACTON	93C	PL B307 247	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALBRECHT	93	ZPHY C57 533	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALBRECHT	93E	ZPHY C60 11	+Ehrlichmann, Hamacher, Hofmann+	(ARGUS Collab.)
ALEXANDER	93B	PL B319 365	+Bebek, Berkelman, Bloom, Browder+	(CLEO Collab.)
AMMAR	93	PRL 71 674	+Ball, Baringer, Coppage, Copty+	(CLEO Collab.)
BARTELT	93	PRL 71 1680	+Csorna, Egyed, Jain, Sheldon+	(CLEO Collab.)
BATTLE	93	PRL 71 3922	+Ernst, Kroha, Kwon, Roberts+	(CLEO Collab.)
BEAN	93B	PRL 70 2681	+Gronberg, Kutschke, Menary, Morrison+	(CLEO Collab.)
BUSKULIC	93D	PL B307 194	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
Also	94H	PL B325 537 (errata)		
BUSKULIC	93K	PL B313 498	+De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
SANGHERA	93	PR D47 791	+Skwarnicki, Stroynowski, Artuso, Goldberg+	(CLEO Collab.)
ALBRECHT	92C	PL B275 195	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92G	ZPHY C54 1	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
ALBRECHT	92L	ZPHY C55 357	+Ehrlichmann, Hamacher, Krueger, Nau+	(ARGUS Collab.)
BORTOLETTO	92	PR D45 21	+Brown, Dominick, McIlwain+	(CLEO Collab.)
HENDERSON	92	PR D45 2212	+Kinoshita, Pipkin, Procario+	(CLEO Collab.)
KRAMER	92	PL B279 181	+Palmer	(HAMB, OSU)
ALBAJAR	91C	PL B262 163	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALBAJAR	91E	PL B273 540	+Albrow, Allkofer, Ankoviak+	(UA1 Collab.)
ALBRECHT	91B	PL B254 288	+Glaeser, Harder, Krueger, Nippe+	(ARGUS Collab.)
ALBRECHT	91C	PL B255 297	+Ehrlichmann, Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	91E	PL B262 148	+Glaeser, Harder, Krueger, Nippe+	(ARGUS Collab.)
BERKELMAN	91	ARNPS 41 1	+Stone	(CORN, SYRA)
"Decays of *B* Mesons"				
FULTON	91	PR D43 651	+Jensen, Johnson, Kagan, Kass+	(CLEO Collab.)
ALBRECHT	90B	PL B241 278	+Glaeser, Harder, Krueger, Nilsson+	(ARGUS Collab.)
ALBRECHT	90J	ZPHY C48 543	+Ehrlichmann, Harder, Krueger+	(ARGUS Collab.)
ANTREASYAN	90B	ZPHY C48 553	+Bartels, Bieler, Bienlein, Bizzeti+	(Crystal Ball Collab.)
BORTOLETTO	90	PRL 64 2117	+Goldberg, Horwitz, Jain, Mestayer+	(CLEO Collab.)
ELSEN	90	ZPHY C46 349	+Allison, Ambrus, Barlow, Bartel+	(JADE Collab.)
ROSNER	90	PR D42 3732		
WAGNER	90	PRL 64 1095	+Hinshaw, Ong, Snyder+	(Mark II Collab.)
ALBRECHT	89C	PL B219 121	+Boeckmannn, Glaeser, Harder+	(ARGUS Collab.)
ALBRECHT	89G	PL B229 304	+Glaeser, Harder, Krueger+	(ARGUS Collab.)
ALBRECHT	89J	PL B229 175	+Glaser, Harder+	(ARGUS Collab.)
ALBRECHT	89L	PL B232 554	+Glaeser, Harder, Krueger, Nippe, Oest+	(ARGUS Collab.)
ARTUSO	89	PRL 62 2233	+Bebek, Berkelman, Blucher+	(CLEO Collab.)
AVERILL	89	PR D39 123	+Blockus, Brabson+	(HRS Collab.)
AVERY	89B	PL B223 470	+Besson, Garren, Yelton+	(CLEO Collab.)
BEBEK	89	PRL 62 8	+Berkelman, Blucher+	(CLEO Collab.)
BORTOLETTO	89	PRL 62 2436	+Goldberg, Horwitz, Mestayer+	(CLEO Collab.)
BORTOLETTO	89B	PRL 63 1667	+Goldberg, Horwitz, Mestayer+	(CLEO Collab.)
ALBRECHT	88F	PL B209 119	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	88K	PL B215 424	+Boeckmann, Glaeser+	(ARGUS Collab.)
ALBRECHT	87C	PL B185 218	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)
ALBRECHT	87D	PL B199 451	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	87I	PL B192 245	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
ALBRECHT	87J	PL B197 452	+Andam, Binder, Boeckmann+	(ARGUS Collab.)
AVERY	87	PL B183 429	+Besson, Bowcock, Giles+	(CLEO Collab.)
BEAN	87B	PRL 58 183	+Bobbink, Brock, Engler+	(CLEO Collab.)
BEBEK	87	PR D36 1289	+Berkelman, Blucher, Cassel+	(CLEO Collab.)
ALAM	86	PR D34 3279	+Katayama, Kim, Sun+	(CLEO Collab.)
ALBRECHT	86F	PL B182 95	+Binder, Boeckmann, Glaser+	(ARGUS Collab.)

PDG	86	PL 170B	Aguilar-Benitez, Porter+	(CERN, CIT+)
CHEN	85	PR D31 2386	+Goldberg, Horwitz, Jawahery+	(CLEO Collab.)
HAAS	85	PRL 55 1248	+Hempstead, Jensen, Kagan+	(CLEO Collab.)
AVERY	84	PRL 53 1309	+Bebek, Berkelman, Cassel+	(CLEO Collab.)
GILES	84	PR D30 2279	+Hassard, Hempstead, Kinoshita+	(CLEO Collab.)
BEHRENDS	83	PRL 50 881	+Chadwick, Chauveau, Ganci+	(CLEO Collab.)