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Theory of CP Violation in B Decays*

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ABSTRACT

Theory of CP violation in B decays is reviewed. For CP asymmetries in B^0 decays, the general formalism is given; the relations with the angles of the unitarity triangle are derived; the sensitivity to new physics is discussed and effects of specific models are described. For CP asymmetries in $B^{\pm}$ decays, the possible mechanisms are described and the difficulties of theoretical estimation are discussed.

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INTRODUCTION

Bottom hadrons will provide us with a rich and novel "laboratory" to study CP violation. Measurements of CP asymmetries in *neutral* B-meson decays into CP eigenstates [1, 2] can provide us with most valuable information. (For reviews see refs. [3, 4].) They will allow us to address three fundamental questions:

(i) Is the Kobayashi-Maskawa phase of the three generation Standard Model the only source of CP violation?

So far, CP violation has been clearly observed only in the measurement of the ϵ-parameter in the K^0 system. While the experimental value of ϵ can be accommodated in the Standard Model, it does not by itself test this model. CP asymmetries in B^0 decays will provide us with an observation of CP violation in a different system and are subject to a clean theoretical interpretation. Thus, they will clearly test whether the single phase of the CKM matrix is the only source of CP violation.

(ii) What are the exact values of the CKM parameters?

The parameters of the CKM matrix are important physical quantities that merit careful measurement. Up to now, the determination of V_{ub} and V_{td} (or, equivalently, of s_{13} and δ in the standard parametrization) is limited in accuracy due to theoretical uncertainties in modeling $b \to u$ transitions and in hadronic matrix elements (f_B). CP asymmetries in B^0 decays provide us with a unique way to measure the CKM parameters. They measure relative phases between various combinations of CKM elements. As these asymmetries are expected to be sizable, systematic errors will probably not obscure the signal. Various consistency checks will further reduce such errors. Most important, the Standard Model predictions for CP asymmetries in B^0 decays are free of hadronic uncertainties, at least in some channels. (For discussions of these predictions for CP asymmetries in B^0 decays, see refs. [5 – 9].)

(iii) Is there new physics in the quark sector?

CP asymmetries in B^0 decays test those aspects of the quark sector that are most sensitive to the possible existence of new physics: CP violation, mixing in the neutral meson systems, and unitarity of the CKM matrix. (For general discussions of CP asymmetries in B^0 decays beyond the Standard Model, see refs. [10 – 12].)

CP asymmetries in *charged* B-meson decays result from a different mechanism and necessarily involve strong interaction phases. Consequently, their theoretical interpretation is subject to hadronic uncertainties. Still, their measurement should be very useful. First, it may provide us with a first demonstration of CP violation outside the K system. Second, we may gain insight into the relevant aspects of strong interactions.

In sections 2–5 of this chapter, we discuss CP asymmetries in B^0 decays: In section 2 we discuss the general formalism; In section 3 we analyze the Standard Model predictions and, in particular, explain the relation between the measured asymmetries and the angles of the unitarity triangle; In section 4 we discuss the sensitivity to new physics of various predictions and relations among the asymmetries; In section 5 we describe how the asymmetries may be modified in specific models beyond the Standard Model. In section 6 we describe the mechanism of CP asymmetries in $B^{\pm}$ decays. Our conclusions are summarized in section 7.

In this chapter we concentrate on the purely theoretical aspects of CP asymmetries in B decays. The experimental prospects for these measurements are discussed in the chapter by I. Dunietz [13]. The reader may find there an analysis of the Standard Model predictions for the numerical values of the asymmetries and a discussion of various methods to extract clean information from additional modes that we do not discuss: angular analysis [14 – 16] of modes such as $B \to \rho\rho$ and isospin analysis [17 – 19] of modes such as $B \to \pi\pi$. We also leave out of our discussion the subjects of CP asymmetries from Dalitz plot distributions [20 – 22] and CP asymmetries in B^0 decays into non-CP eigenstates [23].

GENERAL FORMALISM

We consider a neutral meson B^0 and its antiparticle $\overline{B}^0$. An arbitrary neutral B-meson state,

$$a\,|B_0\rangle + b\left|\overline{B}^0\right\rangle, \tag{1}$$

is governed by the time dependent Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} a \\ b \end{pmatrix}. \tag{2}$$

Here M (the mass matrix) and Γ (which describes the exponential decay of the system) are 2×2 Hermitian matrices. The two mass eigenstates are B_H and B_L (H and L stand for Heavy and Light, respectively):

$$\begin{aligned} |B_L\rangle &= p\,|B_0\rangle + q\left|\overline{B}^0\right\rangle, \\ |B_H\rangle &= p\,|B_0\rangle - q\left|\overline{B}^0\right\rangle. \end{aligned} \tag{3}$$

We neglect the tiny difference in width between B_H and B_L:

$$\Gamma_H = \Gamma_L \equiv \Gamma. \tag{4}$$

($\Delta\Gamma \ll \Gamma$ because it is produced by channels with branching ratios of $\mathcal{O}(10^{-3})$ which contribute with alternating signs [3].) We define:

$$M \equiv (M_H + M_L)/2, \quad \Delta M \equiv M_H - M_L. \tag{5}$$

With $\Gamma_{12} \ll M_{12}$, we have

$$|q/p| = 1. \tag{6}$$

(The arguments for $\Delta\Gamma \ll \Delta M$ are given in section 4.) The amplitudes for the states B_H or B_L at time t can be written as

$$\begin{aligned} a_H(t) =& a_H(0)e^{-(\Gamma/2+iM_H)t}, \\ a_L(t) =& a_L(0)e^{-(\Gamma/2+iM_L)t}. \end{aligned} \tag{7}$$

The proper time evolution of an initially ($t = 0$) pure B^0 $[a_L(0) = a_H(0) = 1/(2p)]$ or $\overline{B}^0$ $[a_L(0) = -a_H(0) = 1/(2q)]$ is given respectively by

$$\begin{aligned} \left|B^0_{\text{phys}}(t)\right\rangle =& g_+(t)\left|B_0\right\rangle + (q/p)g_-(t)\left|\overline{B}^0\right\rangle, \\ \left|\overline{B}^0_{\text{phys}}(t)\right\rangle =& (p/q)g_-(t)\left|B_0\right\rangle + g_+(t)\left|\overline{B}^0\right\rangle, \end{aligned} \tag{8}$$

where

$$\begin{aligned} g_+(t) =& \exp(-\Gamma t/2)\exp(-iMt)\cos(\Delta M t/2), \\ g_-(t) =& \exp(-\Gamma t/2)\exp(-iMt) i \sin(\Delta M t/2). \end{aligned} \tag{9}$$

We are interested in the decays of neutral B's into a CP eigenstate which we denote by f_{CP}. We define the amplitudes for these processes as

$$A \equiv \left\langle f_{CP}|\mathcal{H}|B^0\right\rangle, \quad \overline{A} \equiv \left\langle f_{CP}|\mathcal{H}|\overline{B}^0\right\rangle. \tag{10}$$

We further define

$$\lambda \equiv \frac{q}{p}\frac{\overline{A}}{A}. \tag{11}$$

Then

$$\begin{aligned} \left\langle f_{CP}|\mathcal{H}|B^0_{\text{phys}}(t)\right\rangle =& A[g_+(t) + \lambda g_-(t)], \\ \left\langle f_{CP}|\mathcal{H}|\overline{B}^0_{\text{phys}}(t)\right\rangle =& A(p/q)[g_-(t) + \lambda g_+(t)]. \end{aligned} \tag{12}$$

The time-dependent rates for initially pure B^0 or $\overline{B}^0$ states to decay into a final

CP eigenstate at time t is given by:

$$\Gamma(B^0_{\rm phys}(t)\to f_{CP}) = |A|^2 e^{-\Gamma t}\left[\frac{1+|\lambda|^2}{2}+\frac{1-|\lambda|^2}{2}\cos(\Delta M t)-{\rm Im}\lambda\sin(\Delta M t)\right],$$
$$\Gamma(\overline{B}^0_{\rm phys}(t)\to f_{CP}) = |A|^2 e^{-\Gamma t}\left[\frac{1+|\lambda|^2}{2}-\frac{1-|\lambda|^2}{2}\cos(\Delta M t)+{\rm Im}\lambda\sin(\Delta M t)\right]. \tag{13}$$

We define the time dependent CP asymmetry as

$$a_{f_{CP}}(t)\equiv\frac{\Gamma(B^0_{\rm phys}(t)\to f_{CP})-\Gamma(\overline{B}^0_{\rm phys}(t)\to f_{CP})}{\Gamma(B^0_{\rm phys}(t)\to f_{CP})+\Gamma(\overline{B}^0_{\rm phys}(t)\to f_{CP})}. \tag{14}$$

Then

$$a_{f_{CP}}(t)=\frac{(1-|\lambda|^2)\cos(\Delta M t)-2{\rm Im}\lambda\sin(\Delta M t)}{1+|\lambda|^2}. \tag{15}$$

If, in addition to (6), $|A/\overline{A}|=1$ so that $|\lambda|=1$, then (15) simplifies considerably:

$$a_{f_{CP}}(t)=-{\rm Im}\lambda\sin(\Delta M t). \tag{16}$$

The quantity ${\rm Im}\lambda$ which can be extracted from $a_{f_{CP}}(t)$ is theoretically very interesting since it can be directly related to CKM matrix elements in the Standard Model.

THE STANDARD MODEL

The measurement of the CP asymmetry (14) will determine ${\rm Im}\lambda$ through (15). If $|A/\overline{A}|=1$ (in which case the simpler expression (16) holds), then ${\rm Im}\lambda$ depends on electroweak parameters only, without hadronic uncertainties. The condition which guarantees $|A/\overline{A}|=1$ is easy to find [24]. In the general case, A and $\overline{A}$ can be written as sums of various contributions:

$$A=\sum_i A_i e^{i\delta_i}e^{i\phi_i},$$
$$\overline{A}=\sum_i A_i e^{i\delta_i}e^{-i\phi_i}, \tag{17}$$

where A_i are real, ϕ_i are CKM phases and δ_i are strong phases. Thus, $|A|=|\overline{A}|$ if all amplitudes that contribute to the decay have the same CKM phase, which we will denote by ϕ_D. In such a case

$$\overline{A}/A = e^{-2i\phi_D}. \tag{18}$$

As mentioned above, for $\Gamma_{12} \ll M_{12}$

$$q/p = \sqrt{M_{12}^*/M_{12}} = e^{-2i\phi_M}, \tag{19}$$

where ϕ_M is the CKM phase in the $B - \overline{B}$ mixing. Thus

$$\lambda = e^{-2i(\phi_M+\phi_D)} \implies \mathrm{Im}\lambda = -\sin 2(\phi_M + \phi_D). \tag{20}$$

(Note that each of ϕ_M and ϕ_D is convention dependent, but the sum $\phi_M + \phi_D$ is not.) Indeed, $\mathrm{Im}\lambda$ depends on CKM parameters only. In what follows, we discuss only those processes which, within the Standard Model, are dominated by amplitudes that have a single CKM phase. (For many cases where there are two contributions, one can still cleanly extract the CKM parameters through isospin analysis, if sufficient data is available on the full set of isospin related channels [13, 17 – 19].)

There are two systems of neutral B mesons. For mixing in the B_d [B_s] system $M_{12} \propto (V_{tb}V_{td}^*)^2$ [$(V_{tb}V_{ts}^*)^2$]. Consequently,

$$\left(\frac{q}{p}\right)_{B_d} = \frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}; \qquad \left(\frac{q}{p}\right)_{B_s} = \frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}. \tag{21}$$

There are several types of relevant decay processes. We will mainly concentrate on tree decays. (Where non-spectator processes (exchange or annihilation) contribute, they do so with the same weak phase as the spectator tree diagram and hence are included in the tree amplitudes here.) For decays via quark subprocesses $b \to$

$\overline{u}_i u_i d_j$ which are dominated by tree diagrams,

$$\frac{\overline{A}}{A} = \frac{V_{ib}V_{ij}^*}{V_{ib}^*V_{ij}}. \tag{22}$$

Thus, for B_{d_j} decaying through $\overline{b} \to \overline{u}_i u_i \overline{d}_j$,

$$\mathrm{Im}\lambda = \sin\left[2\arg\left(\frac{V_{ib}V_{ij}^*}{V_{tb}V_{tj}^*}\right)\right]. \tag{23}$$

For decays with a single K_S (or K_L) in the final state, $K - \overline{K}$ mixing is essential because $B^0 \to K^0$ and $\overline{B}^0 \to \overline{K}^0$, and interference is possible only due to $K - \overline{K}^0$ mixing. For these modes

$$\lambda = \left(\frac{q}{p}\right)\left(\frac{\overline{A}}{A}\right)\left(\frac{q}{p}\right)_K, \quad \left(\frac{q}{p}\right)_K = \frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}. \tag{24}$$

We will also mention decay processes $b \to \overline{s}sd_j$ which are dominated by penguin diagrams. For these

$$\frac{\overline{A}}{A} = \frac{V_{tb}V_{tj}^*}{V_{tb}^*V_{tj}}. \tag{25}$$

Note that sign(Imλ) depends on the CP transformation properties of the final state. The analysis above corresponds to CP-even final states. For CP-odd states, Imλ has the opposite sign. In what follows, we give Imλ of CP-even states, regardless of the CP assignments of specific hadronic modes discussed.

CP asymmetries in B^0 decays into CP eigenstates provide a way to measure the three angles of the unitarity triangle independently of each other and without hadronic uncertainties. The unitarity triangle is a simple geometrical representation of the relation

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \tag{26}$$

which results from the unitarity of the three generation CKM matrix: the three complex quantities $V_{id}V_{ib}^*$ form a triangle in the complex plane. The three angles of this triangle are defined by

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right). \qquad (27)$$

The aim is to make enough independent measurements of the sides and angles that this triangle is overdetermined and thus check the validity of the Standard Model. We now give three explicit examples for asymmetries that measure the three angles α, β and γ:

(i) Measuring $\sin(2\beta)$ in $B \to \psi K_S$.

The mixing phase in the B_d system is given in Eq. (21), $(q/p)_{B_d} = (V_{tb}^* V_{td})/(V_{tb}V_{td}^*)$. With a single final kaon, one has to take into account the mixing phase in the K system given in Eq. (24), $(q/p)_K = (V_{cs}V_{cd}^*)/(V_{cs}^* V_{cd})$. The decay phase (22) in the quark subprocess $b \to c\bar{c}s$ is

$$\frac{\overline{A}}{A} = \frac{V_{cb}V_{cs}^*}{V_{cb}^* V_{cs}}. \qquad (28)$$

We get

$$\lambda(B \to \psi K_S) = \left(\frac{V_{tb}^* V_{td}}{V_{tb}V_{td}^*}\right)\left(\frac{V_{cs}^* V_{cb}}{V_{cs}V_{cb}^*}\right)\left(\frac{V_{cd}^* V_{cs}}{V_{cd}V_{cs}^*}\right) \Longrightarrow \mathrm{Im}\lambda = -\sin(2\beta). \qquad (29)$$

(As ψK_S is a $CP = -1$ state, there is an extra minus sign in the asymmetry which we ignore here.) Note that there is a small penguin contribution to $b \to c\bar{c}s$. However, it depends on the CKM combination $V_{tb}V_{ts}^*$ which has, to a very good approximation, the same phase (mod π) as the tree diagram which depends on $V_{cb}V_{cs}^*$. Since both amplitudes have the same weak phase, the analysis is not altered.

(ii) Measuring $\sin(2\alpha)$ in $B \to \pi^+\pi^-$.

The mixing phase in the B_d system is given in Eq. (21). The decay phase (22) for the quark subprocess $b \to u\bar{u}d$ is

$$\frac{\overline{A}}{A} = \frac{V_{ub}V_{ud}^*}{V_{ub}^*V_{ud}}. \tag{30}$$

We get

$$\lambda(B \to \pi^+\pi^-) = \left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\right)\left(\frac{V_{ud}^*V_{ub}}{V_{ud}V_{ub}^*}\right) \Longrightarrow \mathrm{Im}\lambda = \sin(2\alpha). \tag{31}$$

In this case, the penguin contribution is still expected to be small, but it depends on the CKM combination $V_{td}^*V_{tb}$ which has a phase different from that of the tree diagram. Uncertainties due to the penguin contribution can be eliminated using isospin analysis [17], as discussed in the chapter by I. Dunietz [13].

(iii) Measuring $\sin(2\gamma)$ in $B_s \to \rho K_s$.
The mixing phase in the B_s system is given in Eq. (21), $(q/p)_{B_s} = (V_{tb}^*V_{ts})/(V_{tb}V_{ts}^*)$. Due to the final K_S, the mixing phase for the K system has to be taken into account. The quark subprocess is the same as in $B \to \pi\pi$, namely $b \to u\bar{u}d$. We get

$$\lambda(B_s \to \rho K_S) = \left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\right)\left(\frac{V_{ud}^*V_{ub}}{V_{ud}V_{ub}^*}\right)\left(\frac{V_{cs}^*V_{cd}}{V_{cs}V_{cd}^*}\right) \Longrightarrow \mathrm{Im}\lambda = -\sin(2\gamma). \tag{32}$$

The three examples that we gave above demonstrate that the three angles of the unitarity triangle can in principle be measured independently of each other. Perhaps most difficult will be the measurement of γ, since achieving a high luminosity source of B_s will be very difficult. A way to measure γ in B_d decays [26] is discussed in [13], but this too will be a very difficult experiment. In tables I and II we list CP asymmetries for various channels in B_d and B_s decays, respectively. The asymmetries are denoted by $\mathrm{Im}\lambda_{iq}$. The subscript $i = 1, \ldots, 5$ denotes the quark sub-process. The sub-index $q = d, s$ denotes the type of decaying meson, B_q. The list of hadronic final states gives examples only. Other states may be more favorable experimentally. We always quote the CP asymmetry for CP-even states, regardless of the specific hadronic state listed.

TABLE I

CP Asymmetries in B_d Decays

Class (iq)	Quark sub-process	Final state (example)	SM prediction
$1d$	$\bar{b} \to \bar{c}c\bar{s}$	ψK_S	$-\sin 2\beta$
$2d$	$\bar{b} \to \bar{c}c\bar{d}$	$D^+ D^-$	$-\sin 2\beta$
$3d$	$\bar{b} \to \bar{u}u\bar{d}$	$\pi^+\pi^-$	$\sin 2\alpha$
$4d$	$\bar{b} \to \bar{s}s\bar{s}$	ϕK_S	$-\sin 2\beta$
$5d$	$\bar{b} \to \bar{s}s\bar{d}$	$K_S K_S$	0

TABLE II

CP Asymmetries in B_s Decays

Class (iq)	Quark sub-process	Final state (example)	SM prediction
$1s$	$\bar{b} \to \bar{c}c\bar{s}$	$D_s^+ D_s^-$	0
$2s$	$\bar{b} \to \bar{c}c\bar{d}$	ψK_S	0
$3s$	$\bar{b} \to \bar{u}u\bar{d}$	ρK_S	$-\sin 2\gamma$
$4s$	$\bar{b} \to \bar{s}s\bar{s}$	$\eta'\eta'$	0
$5s$	$\bar{b} \to \bar{s}s\bar{d}$	ϕK_S	$\sin 2\beta$

Finally, we mention that the sign of the various asymmetries is predicted within the Standard Model (and not only the relative signs between various asymmetries). Measuring the signs of several asymmetries may serve to test whether the KM phase is indeed the source of CP violation [25].

SENSITIVITY TO NEW PHYSICS

While each of the specific predictions in Tables I and II depends on many ingredients of the Standard Model (see *e.g.* a detailed discussion of $\text{Im}\lambda_{3s} = -\sin 2\gamma$ in ref. [12]), certain relations among asymmetries depend on fewer assumptions [11, 25]. For example, the relation $\text{Im}\lambda_{1d} = \text{Im}\lambda_{2d}$ depends only on the mechanisms of the tree-level decay and of $K-\overline{K}$ mixing (and not on the mechanism of $B-\overline{B}$ mixing or on the unitarity of the CKM matrix). Such relations are likely to hold in many extensions of the Standard Model. Conversely, if they fail to hold, this may imply exactly which ingredients of the Standard Model have to be superseded. To discuss the sensitivity of the analysis to new physics, we divide the various assumptions into five groups, and comment on each of them in turn.

a. In neutral B^0 systems, $\Gamma_{12} \ll M_{12}$.

Within the Standard Model, one can explicitly calculate the two relevant quantities (assuming that a quark-level description is appropriate):

$$\frac{\Gamma_{12}}{M_{12}} = \frac{3\pi}{2}\frac{1}{f_2(y_t)}\frac{m_b^2}{m_t^2} \sim 10^{-2}. \tag{33}$$

$f_2(y_t)$ is a slowly varying function of $y_t \equiv m_t^2/M_W^2$; it assumes values in the range $\{\frac{3}{4}, \frac{1}{4}\}$ for y_t in the range $\{1, \infty\}$. However, it seems that the order of magnitude estimate holds far beyond the Standard Model [3]. For Γ_{12} to be enhanced, one needs a new decay mechanism which significantly dominates over the W mediated tree decay. This is most unlikely; there seems to be no viable model that suggests such a situation. Therefore, a ratio Γ_{12}/M_{12} significantly higher than in Eq. (33) is possible only in models where M_{12} is significantly suppressed. This requires fine-tuning to cancel the known top contribution with some new physics mechanism. Again, we know of no model where a cancellation to two orders of magnitude is predicted. The argument is particularly solid for the B_d system, as it is supported by experimental evidence: $\Delta M/\Gamma \sim 0.7$, while (upper limits on) branching ratios into states which contribute to Γ_{12} are $\lesssim 10^{-3}$.

b. The relevant decay processes (in classes $i = 1,2,3$) are dominated by the Standard Model tree diagrams.

Within the Standard Model, there are contributions from penguin diagrams as well. If the matrix element for the penguin operator is not significantly enhanced, then these amplitudes are suppressed by a factor of $(\alpha_s/12\pi)\ln(m_t^2/m_b^2)$ compared to the tree-level amplitudes. The situation is particularly promising in the $\overline{b} \to \overline{c}c\overline{s}$ processes, where the CKM combinations for the tree and penguin amplitudes carry the same phase. It seems reasonable that for other tree decays (except for $\overline{b} \to \overline{u}u\overline{s}$ which we do not consider here) the effect is within 10% or less [27 – 29]. In models of new physics , violation of this Standard Model assumption is possible if there is a new decay mechanism which competes with the W-mediated tree-level decay. Unlike our discussion of Γ_{12}, the effect will be important even if it is comparable to the Standard Model diagram (and not necessarily dominating over it). However, experimental measurements of rare processes (*e.g.* $B - \overline{B}$ mixing or $B \to X\ell^+\ell^-$ decays) typically constrain the couplings or the scale of the new physics in a way which renders the contribution from the new physics to tree-level processes very small. For example, amplitudes from new physics at the 1 TeV scale typically give $\lesssim 1\%$ of the Standard Model tree amplitude.

c. $K - \overline{K}$ mixing is dominated by box-diagrams with virtual c-quarks.

Even within the Standard Model there is a non-negligible long-distance contribution. The important ingredient is that the relevant CKM *phase* is $(q/p)_K = \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}$. The validity of this assumption holds far beyond the Standard Model: Consider the condition on mixing in the K system from the measurement of the ϵ parameter: $\arg(M_{12}/\Gamma_{12})(\mathrm{mod}\ \pi) = 6.6 \times 10^{-3}$. It implies that, to an excellent approximation, M_{12} and Γ_{12} carry the same phase (mod π). Assuming that the $K \to 2\pi$ amplitude is proportional to $V_{ud}^* V_{us}$, we may use $\arg(q/p)_K = 2\arg(V_{ud}^* V_{us})$ independent of the model for mixing. A new mixing mechanism will not be revealed through CP asymmetries in B^0 decays as long as

$$\arg(V_{ud}^* V_{us}) = \arg(V_{cd}^* V_{cs})(\mathrm{mod}\ \pi). \tag{34}$$

Within any three generation model, Eq. (34) holds to an excellent approximation due to unitarity constraints. Even within extended models, Eq. (34) is likely to hold, but with contrived models it could be violated.

d. $B - \overline{B}$ mixing is dominated by box-diagrams with virtual t-quarks.

The Standard Model box-diagram is suppressed by being fourth-order in the weak coupling and by small mixing angles (the GIM mechanism). Thus, it is not unlikely that new physics contributions, even when suppressed by a high energy scale, will compete with or even dominate over the Standard Model diagram. In many models, such a new mechanism for mixing of neutral B's is suggested (For a review, see ref. [30]). If this is the case, there are two possibilities:

(i) The phase of the new mixing mechanism is the same as that of the Standard Model mechanism. Consequently, the Standard Model predictions will not be violated, even though there is new physics in the relevant processes. As discussed in section 5, in most new physics models there is no reason to expect such a relationship. However the possibility that it could accidentally occur will make it difficult to convert a result in agreement with the Standard Model into bounds on the parameters of theories beyond the Standard Model.

(ii) The phase of the new mixing mechanism is different from the Standard Model mechanism. Consequently, CP asymmetries in B^0 decays may be very different from the Standard Model predictions. They no longer measure the relative phase between the CKM combinations that determine the decay and the mixing. Instead they measure the relative phase between the CKM combination that determines the decay and the phase from new physics that determines the mixing. As these new phases have no experimental constraints, their effect could be rather dramatic, *e.g.* give maximal asymmetry where the Standard Model predicts zero asymmetry.

e. The three generation CKM matrix is unitary.

The relevant unitarity constraints are:

$$\mathcal{U}_{db} \equiv \sum_{k=1}^{3} V_{kb} V_{kd}^* = 0; \quad \mathcal{U}_{sb} \equiv \sum_{k=1}^{3} V_{kb} V_{ks}^* = 0. \tag{35}$$

If the full spectrum of colored fermions consists of the three known generations of quarks, the 3×3 CKM matrix is unitary, and all the constraints hold. Adding sequential quarks (namely, left-handed doublets and right-handed singlets) or non-sequential quarks (*e.g.* $SU(2)_L$ singlets of charge $-1/3$) leads to violation of (35). As emphasized in ref. [11], a small violation of the unitarity constraints usually gives a significant new contribution to $B-\overline{B}$ mixing. (More specifically, if $\mathcal{U}_{db} \neq 0$ [$\mathcal{U}_{sb} \neq 0$], there will be significant contributions from beyond the Standard Model to $B_d-\overline{B}_d$ [$B_s-\overline{B}_s$] mixing.) For CP asymmetries in B^0 decays, this second effect is the one that may give substantial deviations from the Standard Model predictions.

From our general analysis of the assumptions $a-e$ above, the following respective conclusions follow in most models of new physics (see Tables I and II for the various (iq) assignments):

a. λ_{iq} is of the form ($|\lambda_{iq}| = 1$):

$$\lambda_{iq} = e^{-2i[\phi_M^q + \phi_D^i + \phi_K^{iq}]}. \tag{36}$$

The ϕ_M^q-phase depends on the mixing amplitude of the decaying meson. The ϕ_D^i-phase depends on the quark sub-process amplitude. The ϕ_K^{iq}-phase (which differs from zero only for final states with an odd number of neutral kaons) depends on the $K-\overline{K}$ mixing amplitude.

b. For classes $i = 1,2,3$ the ϕ_D^i-phases are given by

$$\phi_D^1 = \arg(V_{cb} V_{cs}^*), \quad \phi_D^2 = \arg(V_{cb} V_{cd}^*), \quad \phi_D^3 = \arg(V_{ub} V_{ud}^*). \tag{37}$$

For classes $i = 4,5$, the dominant direct decay mechanism within the Standard Model is the penguin amplitude. We include them in the tables for completeness, but will not discuss them in detail. A detailed analysis is given in ref. [25].

c. The ϕ_K^{iq} factor is given by:

$$\begin{aligned}\phi_K^{2d} =&\phi_K^{3d} = \phi_K^{5d} = \phi_K^{1s} = \phi_K^{4s} = 0,\\ \phi_K^{1d} =&\phi_K^{4d} = \phi_K^{2s*} = \phi_K^{3s*} = \phi_K^{5s*} = \arg(V_{ud}^* V_{us}).\end{aligned} \tag{38}$$

On the other hand:

d. ϕ_M^q may differ significantly from the Standard Model values, if there are new contributions to the mixing of neutral B's, and if these contributions carry new phases.

e. The unitarity constraints on $\mathcal{U}_{db}$ and $\mathcal{U}_{sb}$ may be significantly violated in models of extended quark sector.

Within the Standard Model, the asymmetries measure angles in the complex plane between various combinations of the charged current mixing matrix, as those determine both b decays and $B_q - \overline{B}_q$ mixing. These angles are calculated within the Standard Model on the basis of direct measurements and unitarity of the CKM matrix. Within models of new physics, unitarity of the charged current mixing matrix may be lost, but this is not the main reason for the asymmetries being modified. The reason is rather that, when $B_q - \overline{B}_q$ mixing has significant contributions from new physics, the asymmetries measure different quantities, namely angles between combinations of elements of the charged current mixing matrix determining b decays and elements of mixing matrices in sectors of new physics (squarks, multi-Higgs, etc.) which determine $B_q - \overline{B}_q$ mixing. In view of these observations, let us examine which of the predictions of Tables I and II are likely to hold and which may be violated with new physics [11, 25].

The predictions

$$\mathrm{Im}\ \lambda_{1d} = \mathrm{Im}\ \lambda_{2d}, \quad \mathrm{Im}\ \lambda_{1s} = \mathrm{Im}\ \lambda_{2s}, \tag{39}$$

do not depend on the mixing mechanism for neutral $B's$. Instead, they depend only on the mechanism for tree-level decays and for $K - \overline{K}$ mixing. They will hold as long as $\phi_D^1 + \phi_K^{1q} = \phi_D^2 + \phi_K^{2q}$. As explained above, this relation will hold in all but some very contrived models with both new mechanism for $K - \overline{K}$ mixing and extended quark sector.

The predictions

$$\text{Im } \lambda_{1d} = \text{Im } \lambda_{4d}, \quad \text{Im } \lambda_{1s} = \text{Im } \lambda_{4s}, \tag{40}$$

do not depend on the mixing mechanism for neutral $B's$. Instead, they depend only on the mechanism for direct decays and the unitarity constraint $\mathcal{U}_{sb} = 0$. They are likely to be violated in any model with $\mathcal{U}_{sb} \neq 0$. Similarly, certain relations between asymmetries in classes $i = 2, 3$ and $i = 5$ will be violated if $\mathcal{U}_{db} \neq 0$.

The prediction

$$\text{Im } \lambda_{1s} = 0 \tag{41}$$

depends on the mechanism for tree-level decays, on the unitarity constraint $\mathcal{U}_{sb} = 0$ and on the mechanism for B_s mixing. It is likely to be violated in models with new phases in $B_s - \overline{B}_s$ mixing.

The predictions

$$\text{Im } \lambda_{2d} = -\sin(2\beta), \quad \text{Im } \lambda_{3d} = \sin(2\alpha), \tag{42}$$

depend on the mechanism for tree-level decays, on the unitarity constraint $\mathcal{U}_{db} = 0$ and on the mechanism for B_d mixing. They are likely to be violated in models with new phases in $B_d - \overline{B}_d$ mixing.

Finally, we note that the three angles deduced from measurements of the Im λ_{1d}, Im λ_{3d} and Im λ_{3s} will sum up to 180^o whenever the amplitude for $B_s - \overline{B}_s$ mixing is real [11]. This is independent of whether they correspond to the angles of the unitarity triangle or not.

We now briefly survey relevant models of new physics. As explained in previous sections, we look for violation of the unitarity constraints:

$$\mathcal{U}_{db} = 0; \quad \mathcal{U}_{sb} = 0, \tag{43}$$

and, more important, for contributions to $B_q - \overline{B}_q$ mixing which are different in phase and at least comparable in magnitude to the Standard Model contribution:

$$M_{12}^{t}(B_q) = \frac{G_F^2}{12\pi^2}\eta M_B(B_B f_B^2) M_W^2 y_t f_2(y_t)(V_{tb}^* V_{tq})^2. \tag{44}$$

1. **Four quark generations** [31 − 34]:

There are no new tree-level contributions to b decays. Thus, Γ_{12} remains unmodified and the direct tree-level decays are still dominated by the W-mediated diagrams. Unitarity of the CKM matrix is violated:

$$\mathcal{U}_{qb} = -V_{t'b} V_{t'q}^*. \tag{45}$$

There could be significant new contributions to $B_q - \overline{B}_q$ mixing. For example, a box-diagram with virtual t' quarks contributes:

$$M_{12}^{t'}(B_q) = \frac{G_F^2}{12\pi^2}\eta M_B(B_B f_B^2) M_W^2 y_{t'} f_2(y_{t'})(V_{t'b}^* V_{t'q})^2. \tag{46}$$

The full (4×4) mixing matrix has three independent phases, which could appear in M_{12}.

2. Z**-mediated flavor changing neutral currents (FCNC)** [35 − 36]:

There are tree-level Z-mediated contributions to b decays. Experimental constraints imply that they are below 5% of the tree-level W-mediated diagram. Although Γ_{12} has new contributions from Z mediated diagrams, it is not expected to be enhanced. The direct decays are still dominated by the W-mediated tree diagrams. Unitarity of the CKM matrix is violated:

$$\mathcal{U}_{qb} = U_{qb}, \tag{47}$$

where U_{qb} is a non-diagonal Z-coupling. There could be significant new contributions to $B_q - \overline{B}_q$ mixing from tree-level diagrams:

$$M_{12}^{Z}(B_q) = \frac{\sqrt{2}G_F}{12}\eta M_B(B_B f_B^2)(U_{qb}^*)^2. \tag{48}$$

There are new independent phases in the neutral current mixing matrix which could appear in M_{12}.

3. **Multi-Higgs doublets with natural flavor conservation (NFC):**

There are tree-level ϕ^+-mediated contributions to b decays. Experimental limits on the mass of the charged Higgs imply that they are negligible. Thus, there is no significant effect on Γ_{12} and on direct decays. Unitarity of the CKM matrix is maintained. There could be significant new contributions to $B_q - \overline{B}_q$ mixing from box-diagrams with charged Higgs. In a general n-doublet model with NFC, the couplings of the physical charged scalars to quarks are given by [37]:

$$\mathcal{L} = \sum_{k=2}^{n} \frac{g_2 \phi_k^+}{2\sqrt{2}M_W}\overline{U}[-(Y_{1k}/Y_{11})M_u V(1-\gamma_5)+(Y_{2k}/Y_{21})VM_d(1+\gamma_5)]D+h.c. \tag{49}$$

Y is the matrix that rotates the mass eigenstates charged scalars to the interaction eigenbasis. Without loss of generality we took ϕ_1^+ to be the Goldstone boson. The Y-matrix introduces new phases which are not related to those of V_{CKM}. However, the leading contribution from ϕ_k^+-exchange diagrams to $B - \overline{B}$ mixing comes from the term proportional to m_t. This gives $(Y_{1k}V_{td})(Y_{1k}V_{tb})^*$, and has exactly the same phase as the Standard Model W-exchange contribution. Consequently, $\arg(M_{12})$ remains unmodified.

It is amusing to note that in the multi-scalar models with NFC and with spontaneous CP violation (SCPV), where $\delta_{KM}=0$ (so that the unitarity triangle becomes a line), CP asymmetries in classes $i=1,2,3$ all vanish. (This was shown in detail for $B\to\psi K_S$ in ref. [38]. A more general discussion of the $\delta_{KM}=0$ case is given in ref. [10].) However, it seems that with the new limits on scalar masses from LEP, this class of models is phenomenologically excluded.

4. **Left-Right Symmetry (LRS)** [39 – 40]:

There are tree-level W_R-mediated contributions to b decays. Experimental limits on the mass of W_R imply that they are negligible. Thus, there is no significant effect on Γ_{12} and on the direct decays. Unitarity of the CKM matrix is maintained. The experimental limits on $M(W_R)$ from $K-\overline{K}$ mixing and the relations between the mixing matrices for W_L and W_R interactions imply that there could be no significant new contributions to $B_q-\overline{B}_q$ mixing. The only way to evade these conclusions is by giving up the left-right symmetry (namely, a model of $SU(2)_L\times SU(2)_R\times U(1)_{B-L}$ gauge symmetry but no discrete $L\leftrightarrow R$ symmetry), and even then one needs to fine-tune the quark sector parameters.

5. **Supersymmetry (SUSY)** [41]:

There are no new tree-level contributions to b decays. Thus, Γ_{12} remains unmodified and the direct tree-level decays are still dominated by the W-mediated diagrams. Unitarity of the CKM matrix is maintained. There could be significant new contributions to $B_q-\overline{B}_q$ mixing from box-diagrams with intermediate gluinos and squarks. Whether these box diagrams carry phases that are different from those of the Standard Model box diagrams depends on the specific SUSY model. In the *minimal* SUSY model, only left-handed squarks (namely, superpartners of left-handed quarks) contribute. The couplings $\tilde{g}\tilde{d}_{Li}\tilde{d}_{Lj}$ are proportional to the CKM element V_{ij} and thus no new phases are introduced:

$$M_{12}^{\tilde{g}}(B_q)=\frac{\alpha_s^2}{27m_{\tilde{g}}^2}Bf_B^2M_B(V_{td}V_{tb}^*)^2\Delta S_t(m_{\tilde{d}},m_{\tilde{b}},m_{\tilde{g}}). \tag{50}$$

The function ΔS_t can be found, for example, in ref. [30]. Thus CP asymmetries are not modified in minimal SUSY models. However, in less restrictive SUSY models, there are contributions from box-diagrams with right-handed squarks as well. The mixing matrices are not related to V_{CKM} and carry, in general, new phases [42]. We emphasize that (unlike our discussion of LRS models), the difference between minimal and extended SUSY models is only in simplicity and predictive power, but not in the basic theoretical principles, and thus extended models are not less motivated than the minimal ones.

6. **"Real Superweak" models** [10]:

This generic framework assumes that $\Delta B = 1$ processes are dominated by the Standard Model amplitudes, but $\Delta B = 2$ processes may have significant new contributions. The only assumption additional to our general discussion is that these new contributions are real. This means that the phases from the direct decays ($\overline{A}/A$) remain the same as in the Standard Model. As for the mixing, while the phase in B_s mixing $(q/p)_{B_s}$ remains the same, the phase in B_d mixing $(q/p)_{B_d}$ is reduced. Consequently, this model predicts no modification of the Standard Model prediction for asymmetries in B_s decays; a reduction in the asymmetry in $B \to \psi K_S$; and a modification (in either direction) of the asymmetry in $B \to \pi^+\pi^-$. This model demonstrates a general feature noted in ref. [11]: Even though the measurements of $B \to \psi K_S$ and $B \to \pi^+\pi^-$ do not measure β and α anymore, the angles deduced from these measurements will sum up with γ (deduced correctly from $B_s \to \rho K_S$) to 180^o. This is guaranteed by the B_s mixing amplitude being real.

A summary of our conclusions is given in Table III. The second column describes, for each model, whether unitarity of the three generation CKM matrix is maintained (a triangle) or violated (a quadrangle). The third column gives an example of a new contribution to $B_q - \overline{B}_q$ mixing. Unless otherwise mentioned, the contribution could be large and carry new phases.

TABLE III

Effects of new physics on CP asymmetries

Model	CKM Unitarity	$B-\bar{B}$ Mixing	SM Predictions for A^{CP}
SM		t W W t	
Four Quark Generations	$V_{t'd}V^*_{t'b}$	t′	Modified
Multi-Scalar with NFC (General)		ϕ^+ No New Phases	Unmodified
(+ SCPV)			All Asymmetries Vanish
Z-Mediated FCNC	U^*_{db}	Z	Modified
LRS		W_R Small	Unmodified
SUSY (General)		$\tilde{g}$ $\tilde{q}_L,\tilde{q}_R$ $\tilde{q}_L,\tilde{q}_R$ $\tilde{g}$	Modified
(Minimal)		$\tilde{g}$ $\tilde{q}_L$ $\tilde{q}_L$ $\tilde{g}$ No New Phases	Unmodified
"Real Superweak"		Real	Modified for B_d Unmodified for B_s

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CP VIOLATION IN CHARGED B DECAYS

One of the outstanding questions on CP violation is whether all CP violation phenomena are due to neutral particle mixing, as predicted by the superweak class of theories, or instead whether there are direct CP violating decays. Measurement of a non-vanishing value for the parameter ϵ' in the K-system would give evidence for the latter conclusion, but is proving an exceedingly difficult task [43]. An alternate way to study this question is via the search in charged B decays for CP violating differences of the form

$$a_f = \frac{\Gamma(B^+ \to f) - \Gamma(B^- \to \overline{f})}{\Gamma(B^+ \to f) + \Gamma(B^- \to \overline{f})} \tag{51}$$

where f is any final state channel and $\overline{f}$ is its CP conjugate. Although CPT symmetry requires that the total B^+ and B^- decay widths are the same, specific channels or sum over channels can contribute to asymmetries of the form (51). The conditions for this to occur are quite simple. There must be interference between two separate amplitudes that contribute to the decay $B^+ \to f$ with different weak phases *and* with different strong phase shifts (induced from final state rescattering effects). To see this, let us rewrite Eq. (15) for the case of two contributions:

$$\begin{aligned} A(B^+ \to f) &= A_1 e^{i(\delta_1+\phi_1)} + A_2 e^{i(\delta_2+\phi_2)} \ , \\ A(B^- \to \overline{f}) &= A_1 e^{i(\delta_1-\phi_1)} + A_2 e^{i(\delta_2-\phi_2)} \ . \end{aligned} \tag{52}$$

Again, the quantities A_1 and A_2 are real, the phases $\delta_{1,2}$ represent strong interaction phase shifts while $\phi_{1,2}$ are the weak interaction phases (arising from the CKM matrix in the Standard Model). A little algebra then shows that

$$a_f \propto A_1 A_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \ . \tag{53}$$

Within the Standard Model, it was recognized by Bander, Silverman and Soni [44] that these conditions can readily be met in three types of B decays:

(i) CKM suppressed B decays. The tree amplitudes for $b \to su\overline{u}$ (or $b \to du\overline{u}$) can interfere with penguin type processes which lead to the same quark content for the final states.

(ii) CKM forbidden B decays. In the channels $b \to sd\overline{d}$, $b \to dd\overline{d}$, $b \to ss\overline{s}$ and $b \to ds\overline{s}$, which have no tree contributions, there can still be asymmetries due to the interference of penguin contributions with different quarks in the loop. In the Standard Model there are three such contributions, corresponding to the three different charge 2/3 quarks. For example, in $b \to ds\overline{s}$

$$A_{b\to ds\overline{s}} = v_{ud}A_{u,ds\overline{s}} + v_{cd}A_{c,ds\overline{s}} + v_{td}A_{t,ds\overline{s}} \tag{54}$$

where v_{xd} is the CKM combination

$$v_{xd} = V_{xb}^{*}V_{xd} \tag{55}$$

and $A_{x,ds\overline{s}}$ is the corresponding penguin amplitude (including the strong phase shift). Similar expressions hold for the other three decay modes mentioned above. The unitarity of the CKM matrix requires

$$v_{uq} + v_{cq} + v_{tq} = 0 \ . \tag{56}$$

It is conventional to use this constraint to eliminate v_{tq} and thus rewrite, for the above example,

$$A_{b\to ds\overline{s}} = v_{ud}\Delta_{ut}(ds\overline{s}) + v_{cd}\Delta_{ct}(ds\overline{s}) \ . \tag{57}$$

This then leads to an asymmetry

$$a_{ds\overline{s}} \propto \mathrm{Im}\,(v_{ud}^{*}v_{cd})\,\mathrm{Im}\,(\Delta_{ut}^{*}\Delta_{ct}) \tag{58}$$

provided the quantities Δ_{ct} and Δ_{ut} have different strong final state phases. The phases of the penguin amplitudes can be evaluated by examining the various possible cuts of the diagrams. If the u and c quarks were degenerate, the two contributions Δ_{ut} and Δ_{ct} would be identical and the asymmetry would vanish.

Since the penguin amplitudes are each of order α_s it is clear that the penguin-penguin interference term is of order α_s^2. Thus a consistent perturbative calculation must take into account all other order α_s^2 contributions to the rate [45]. The use of perturbation theory in α_s is argued to be reasonable because the processes are dominated by the kinematic scale $(m_b - m_\ell) \approx m_b$ and α_s at this peak is a small quantity.

(iii) Radiative B decays. The mechanism for CP asymmetries is similar to that of the pure penguin cases discussed above, except that the leading contribution to the decay is an electromagnetic penguin.

A fourth case of particular interest [26, 46] is the channel $B \to D^0_{CP}K$ where D^0_{CP} is defined by its decay to a CP eigenstate. Here interference between the D^0 and $\overline{D}^0$ tree contributions can give rise to CP violation. This channel could provide a measurement of the angle γ of the unitarity triangle. This is discussed in further detail in [13].

Detailed studies of expected asymmetries in charged B decays for classes (i) and (ii) above have been recently carried out by Gérard and Hou [47] and by Simma, Eilam and Wyler [48]. Both groups reach similar conclusions; namely, $a_{su\bar{u}}$, $a_{sd\bar{d}}$ and $a_{ss\bar{s}}$ are a few tenths of a percent, while for the rarer processes $a_{dd\bar{d}}$ and $a_{ds\bar{s}}$ could be as large as a few percent. Earlier estimates based on model calculations [49] give larger asymmetries but the result is highly model dependent. Estimates of asymmetries in baryonic modes are given in ref. [50]. Asymmetries in radiative B decays have been studied by Soares [51], finding $a_{s\gamma} \sim (1-10) \times 10^{-3}$ and $a_{d\gamma} \sim (1-30) \times 10^{-2}$.

Most of the calculations quoted above give asymmetries for particular quark processes. There remains the problem of how to convert these numbers into reliable estimates for rates and asymmetries in particular exclusive (few body) channels. Each configuration of final hadrons corresponds to some integral over quark kinematics, but unfortunately we have no way to reliably determine the weighting of that integral. Since the calculated quark-level asymmetries depend on the momentum transfer to the $q\bar{q}$ pair and even change sign as a function of this variable in some cases, it is very difficult to convert the quark estimates into estimates for exclusive hadron processes. Furthermore, because of the dependence of the asymmetry on the difference of strong phases as well as that of the weak phases, calculations are sensitive to other aspects of hadronization. In the quark diagram calculation, the long-range final state hadron-hadron interaction phase shifts are ignored, except in the sense that final-state interactions which involve quark-antiquark annihilation processes are included in the absorptive part of the penguin processes. The assumption of small final-state phase effects from hadronization, known as the factorization assumption, is built into the calculations but has not yet been well tested. Wolfenstein has argued [52] that hadronization can result in final-state phase shifts which could decrease the resulting asymmetries compared to the quark-diagram perturbative calculations. This question remains an open one.

Even without further suppression due to such effects, the predictions of refs. [47] and [48] suggest that the CP violations in charged B decays predicted by the Standard Model will be extremely difficult to observe, requiring of order 10^{10} B's for exclusive $b \to s$ modes and of order 10^{9} B's for exclusive $b \to d$ modes. In ref. [47] it is suggested that this can be improved to perhaps as low as 10^{7} B's if one can sum all two-body or quasi two-body $b \to ds\bar{s}$ modes, but the experimental difficulties of such a semi-inclusive measurement may defeat this theoretical improvement. The situation is even more difficult for the radiative decays [51], which give comparable asymmetries but have lower branching ratios.

Although the uncertainties inherent in the calculations described above leave some small possibility of larger effects (see for example the model predictions of ref. [49]), it seems to the present authors that the calculations are sufficiently reliable that asymmetries an order of magnitude *larger* than predicted in refs. [47, 48, 51] would have to be interpreted as evidence for some CP violating mechanism that arises from sources beyond the Standard Model. Various "beyond standard" models contain novel CP violating decay mechanisms which could be comparable to the

Standard Model penguin contributions. For example, with four quark generations there is a penguin diagram with an intermediate t' which depends on additional phases of the 4×4 mixing matrix; in models with Z-mediated flavor changing neutral currents there is a tree diagram which depends on new phases in the neutral current mixing matrix.

The net conclusion of this section is unfortunately that with regard to the charged B decays the situation is not unlike that for ϵ' of the K system. The Standard Model predicts a small effect that will be experimentally very difficult to measure. However, any program of physics for a B-factory should certainly attempt to measure as many different asymmetries of the form (51) as possible. Any large non-zero result could provide a clue to physics beyond the Standard Model.

CONCLUSIONS

CP violation is one of the least understood aspects of the Standard Model; Its observation in B decays is crucial in testing the Standard Model picture of CP violation arising solely from the KM phase. Particularly promising are CP asymmetries in neutral B decays into CP eigenstates which are subject to clean theoretical interpretation and seem to be experimentally most accessible. CP asymmetries in charged B decays would demonstrate the existence of direct CP violation but involve theoretical uncertainties and experimental difficulties. The measurement of CP asymmetries in B decays should constitute a whole program: the more classes of asymmetries measured, the more precisely we determine the CKM parameters within the Standard Model, and the better we understand the detailed nature of new physics which may account for deviations from the Standard Model predictions.

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