

Detecting new physics from CP -violating phase measurements in B decays

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In order to detect new physics using only CP -violating phase measurements in B decays, it is necessary to measure a phase factor which is small in the standard model, in addition to the usual large phases β and γ . We also point out that identifying violations of the unitarity of the CKM matrix is very difficult, and cannot be done with phase measurements alone. [S0556-2821(97)03907-6]

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The major goal of future experiments on B mesons is to measure CP violation [1] to test the standard model (SM) based on the Cabibbo-Kobayashi-Maskawa (CKM) matrix [2], and to detect possible evidence for physics beyond the SM. Several articles have discussed this issue focusing on tests of the general assumptions behind the SM predictions [3,4]. More specific predictions can be made by concentrat-

ing on particular examples of physics beyond the SM [5,6]. Here, we discuss what can be learned exclusively from precision measurements of CP -violating phases in B decays (without making use of other quantitative information), if the new effects are not dominant.

In a standard notation, the CKM matrix can be expanded in powers of the Cabibbo angle $\lambda = \sin\theta_C$, as [7]

$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3[\rho - i\eta(1 - \frac{1}{2}\lambda^2)] \\ -\lambda & 1 - \frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1 + i\eta\lambda^2) \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \quad (1)$$

with the expansion truncated when unitarity is satisfied to order λ^3 for the real part and to order λ^5 for the imaginary part. We will assume the general hierarchical structure of Eq. (1), but there are no assumptions about magnitudes other than that ρ , η , and A are less than unity. In fact, some of our analysis does not even depend on the approximate magnitudes of the V_{ub} , V_{td} , and V_{ts} matrix elements, which are poorly measured.

It is pointed out in an article by Aleksan, Kayser, and London [8] that the matrix contains only four independent phases which may, in principle, be determined from CP -violating experiments. While they emphasize the possibility of reconstructing the matrix from these four phases, our goal is to use them to detect new physics. In the SM, only two of these phases are large; these are essentially the ones usually identified as β and γ . With our weak constraints on ρ and η , the angles β and γ are only poorly constrained. Therefore, these measurements by themselves provide only a weak test of the CKM model. We recall that, in the standard analysis, one combines the measurements of $|V_{ub}|$, $|V_{td}|$, and the CP violation in the neutral Kaon system to constrain the allowed values of β and γ [9]. New physics would then show up through novel correlations between different experiments [10,11]. Our major emphasis is on what

could be learned by attempts to measure a third phase ϵ (not to be confused with the parameter in K decays) which is expected to be much smaller [8].

We follow Ref. [8] and define the two large phases as

$$\beta = \arg\left(-\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*}\right), \quad (2)$$

$$\gamma = \arg\left(-\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}\right). \quad (3)$$

Within the SM, any other large phase we might choose will differ from these only by a term of order ϵ , defined as

$$\epsilon = \arg\left(-\frac{V_{cs}^*V_{cb}}{V_{ts}^*V_{tb}}\right). \quad (4)$$

The last phase needed,

TABLE I. CP -violating asymmetries in B_d decays.

Class	Subprocess	Channel	CP asymmetry
1d	$\bar{b} \rightarrow \bar{c}c\bar{s}$	ψK_S	$-\sin(2\beta - \theta_d)$
2d	$\bar{b} \rightarrow \bar{c}c\bar{d}$	$D^+ D^-$	$-\sin(2\beta - \theta_d)$
3d	$\bar{b} \rightarrow \bar{u}u\bar{d}$	$\pi^+ \pi^-$	$-\sin(2\beta + 2\gamma - \theta_d)$
4d	$\bar{b} \rightarrow \bar{s}s\bar{s}$	ϕK_S	$-\sin(2\beta + 2\epsilon - \theta_d)$

$$\epsilon' = \arg\left(-\frac{V_{ud}^* V_{us}}{V_{cd}^* V_{cs}}\right), \quad (5)$$

is much smaller than the others, in the SM.

Aleksan, Kayser, and London now make the important point that, to a good approximation, we can check the CKM model from the equation [8]

$$\sin\epsilon \simeq \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{\sin\beta \sin\gamma}{\sin(\beta + \gamma)} \simeq \lambda^2 \eta, \quad (6)$$

where the last equality follows from Eq. (1). The approximation involves corrections which, percentagewise, are at most of order λ^2 . The power of this relation lies in the fact that the ratio $|V_{us}/V_{ud}|$ is known to high precision. Similar relations may be derived using other magnitude ratios, such as $|V_{cd}/V_{cs}|$, which are not so well determined. There are two other sets of expressions involving only β , γ , and ϵ , but they require the knowledge of $|V_{ub}|$ or $|V_{td}|$. We note that the validity of Eq. (6) rests on two pillars. On the one hand, it assumes that the extraction of the angles was not inhibited by new physics effects in B_d - \bar{B}_d , or B_s - \bar{B}_s mixing. On the other hand, it explicitly uses unitarity when relating the angles with the magnitudes of CKM matrix elements.

We now turn to the use of Eq. (6) to detect physics beyond the standard model. In Tables I and II we list a set of CP violation experiments and indicate what is measured in terms of β , γ , and ϵ . The only new physics effects that we include are nonunitarity of the CKM matrix and new phase contributions to B_d - \bar{B}_d and B_s - \bar{B}_s mixing, specified by θ_d and θ_s , respectively [12]. These new phases are the only contributions in superweaklike theories, and are expected to be important in many other extensions of the SM. Unitarity is not assumed in calculating these CP asymmetries, but it is assumed that the decays are dominated by intermediate W bosons, and that there are no detectable new phases in the K system. We have classified the decays as in Ref. [4]. Decays based on the quark subprocess $\bar{b} \rightarrow \bar{u}u\bar{s}$ have not been included for they have similar contributions from tree and penguin diagrams. Similarly, those decays involving the quark subprocess $\bar{b} \rightarrow \bar{s}s\bar{d}$ were dropped, since they are likely

TABLE II. CP -violating asymmetries in B_s decays.

Class	Subprocess	Channel	CP asymmetry
1s	$\bar{b} \rightarrow \bar{c}c\bar{s}$	$D_s^+ D_s^-$	$\sin(2\epsilon + \theta_s)$
2s	$\bar{b} \rightarrow \bar{c}c\bar{d}$	ψK_S	$\sin(2\epsilon + \theta_s)$
3s	$\bar{b} \rightarrow \bar{u}u\bar{d}$	ρK_S	$-\sin(2\gamma - 2\epsilon - \theta_s)$
4s	$\bar{b} \rightarrow \bar{s}s\bar{s}$	$\eta' \eta'$	$\sin(\theta_s)$

to be more affected by penguin diagrams with virtual charm and up quarks. Note that the asymmetries 1 and 2 are equal [3]. This is due to the K - \bar{K} mixing phase which is mandatory in order for the result to be invariant under a rephasing of the s and d quarks.

The first channels to be measured at B factories are ψK_S and $\pi^+ \pi^-$. This will permit a correct determination¹ of 2γ , but 2β appears always in connection with θ_d . The first measure of ϵ is likely to come from process (2s), $B_s \rightarrow \psi K_S$. A failure of Eq. (6) would then mean that $\theta_s \neq 0$, and we did not correctly measure ϵ , or that $\theta_d \neq 0$, and we have the wrong value for β , or that the values of ϵ and β are correct, but the CKM matrix is not 3×3 unitary, so that the sides and angles are not related in the expected way. It could be a combination of all three. Of course, as was stressed by Nir and Silverman [3], if the asymmetry of process (2s) is much larger than λ^2 , there must be a new contribution θ_s to the B_s - \bar{B}_s mixing phase. Our analysis is directed to smaller violations of Eq. (6).

For the moment we concentrate on the mixing effects assuming that the nonunitarity is less important. We will come back to it later on. To distinguish the cases of $\theta_s \neq 0$ from those of $\theta_d \neq 0$, it is necessary to learn about the phases of V_{ts} or V_{td} from sources other than mixing. The most likely processes are the decays of the form $\bar{b} \rightarrow \bar{s}s\bar{s}$, in classes (4d) and (4s). These are expected to be dominated by a penguin graph proportional to $V_{tb}V_{ts}^*$. Note that the penguin graphs involving u and c quarks are suppressed by an extra power of λ^2 . The asymmetry of (4d) compared to (1d) gives the true value of ϵ . This yields two pieces of information. We can insert this correct value of ϵ into Eq. (6), so that a failure of the equality must then be due to θ_d . Moreover, if this value of ϵ differs from that deduced from (2s), then there is a nonzero value of θ_s , which could also be directly detected from the asymmetry of (4s).

If the new physics is superweak [16], it might make a similar contribution to B_d - \bar{B}_d and B_s - \bar{B}_s mixing. Suppose that contribution is of the order of $\Delta M(B_d)$. The result is a large value for θ_d , but a value of order λ^2 for θ_s . To detect such a value for θ_s requires determining ϵ to an accuracy of a fraction of λ^2 . From the present analysis, a large value of θ_d has the effect of giving the wrong value of β to insert in Eq. (6), and thus changes the calculated value of ϵ by a term of order λ^2 . This again requires determining ϵ to high accuracy. Thus, in the absence of quantitative knowledge of the magnitudes of V_{ub} and V_{td} , the use of CP -violating phases alone to detect new physics requires very precise measurements.

¹It is well known that the use of the $\pi^+ \pi^-$ decay is uncertain due to the presence of a small penguin contribution [13]. This can be overcome measuring isospin-related channels [14], though that requires the experimentally challenging detection of π^0 's. Using the $K\pi$, SU(3)-related channels [15] will be easier, since most proposed detectors have good charged meson identification. It should be noted that our use of β and γ is to determine ϵ from Eq. (6), so that we do not require extremely accurate values of β and γ in order to obtain ϵ to a sufficient accuracy.

While these arguments hold if the new physics is super-weak [16], in many theories there may be significant new contributions to $b \rightarrow \bar{s}s\bar{s}$. The importance of such new penguin-type diagrams has been emphasized in discussions of the decay $b \rightarrow s\gamma$ [17] and, more recently, in the comprehensive study of Gronau and London [6].

We now turn to the question of identifying violations of the unitarity of the 3×3 CKM matrix, as can occur, for example, in models with extra quarks. It is often suggested that one can test unitarity by measuring three large phases $\bar{\beta}$, $\bar{\alpha}$, and $\bar{\gamma}$ from reactions (1d), (3d), and (3s), respectively, and see if they add up to π . Following Ref. [8], we have emphasized that there are only two large angles, β and γ , and that the third relevant angle is the small angle ϵ . Unitarity then implies Eq. (6). However, the failure of Eq. (6) can be attributed to the presence of θ_d , as discussed above, and thus does not imply a failure of unitarity. Indeed, a large class of theories, including those in which unitarity is violated, give a significant value of θ_d . We thus reach the conclusion that it is impossible to identify a violation of unitarity simply from measurements of three independent CP violation phases.

We stress that deviations from unitarity will show up in a failure of SM relations involving *both* angles and magnitudes. In particular, the relation $\bar{\alpha} + \bar{\beta} + \bar{\gamma} = \pi$ does *not* test unitarity [18]. Such a test will only arise when one confronts these angles with the relevant magnitudes in the unitarity triangle.

Moreover, clearly identifying unitarity violations, even in principle, requires precise knowledge of CKM magnitudes other than the Cabibbo angle. It is then possible to derive various relations between angles and magnitudes independent of Eq. (6). However, unless both $|V_{td}|$ and $|V_{ub}|$ are

included, it is still necessary to have a measurement of the small phase ϵ . An example of such a relation is

$$\sin\epsilon \approx \left\{ 1 - \left| \frac{V_{cs}V_{cb}}{V_{ts}V_{tb}} \right| \right\} \tan\gamma. \quad (7)$$

This would distinguish the two effects. There is a similar relation involving the same magnitudes and β , but that would not solve the problem of disentangling θ_d from non-unitarity. Note that the order to which we have taken the Wolfenstein parametrization of Eq. (1), is not good enough to confirm this relation. This is due to the fact that we need to know $|V_{cs}V_{cb}|/|V_{ts}V_{tb}|$ to order λ^2 , requiring very precise measurements.

In conclusion, we have shown that testing the SM exclusively through CP -violating asymmetries in B decays, requires the measurement of a small phase ϵ , in addition to the usual large phases β and γ . Unless there is a large new phase in B_s - \bar{B}_s mixing [3], the detection of new physics in this way requires a measurement of ϵ with a precision of order $\eta\lambda^2$, unlikely to be reached in the experiments currently planned. We have shown how this measurement could be used to determine new phases θ_d and θ_s in B - \bar{B} mixing, if these are the only new physics effects. In models that are not super-weak other new physics effects might also be significant.

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