New physics effects in *CP*-violating *B* decays

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Contributions to B-$\overline{B}$ mixing from physics beyond the standard model may be detected from CP-violating asymmetries in B decays. There exists the possibility of large new contributions that cannot be detected by first generation experiments because of a discrete ambiguity. Some possible strategies for resolving this are discussed. [S0556-2821(98)04311-2]

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A major goal of the experiments on B mesons is to check the standard model, or conversely, to discover new physics. In many models beyond the standard model, there exist new contributions to B-$\overline{B}$ mixing [1]. In this paper, we assume that this is the only new physics and discuss strategies to detect it. An important conclusion is that even large new contributions due to B_d-$\overline{B_d}$ mixing may be difficult to detect. Of course in some models, the existence of such large new contributions might imply other deviations from the standard model such as the rates for rare decay processes [2].

The first information on B-$\overline{B}$ mixing comes from the measurement of Δm or $x_d=\Delta m/\Gamma$. This is proportional to

$$A^2[(1-\rho)^2+\eta^2]B_B\eta_2 f_B^2$$

where $B_B\eta_2 f_B^2$ involves the hadronic matrix element. Given the hadronic uncertainty and conservative limits on the Cabibbo-Kobayashi-Maskawa (CKM) matrix parameters (ρ,η) the standard model predicts x_d only within a factor of about ten. The experimental result $x_d=0.7$ fits very nicely but provides weak constraints on new physics.

The next information, a major goal of B factories, is the phase of M_{12} in the standard phase convention. This is given by $2\widetilde{\beta}$ and determined from measuring the CP-violating asymmetry $\sin 2\widetilde{\beta}$ in the decay $B\to\psi K_S$. In the standard model $\widetilde{\beta}=\beta$, the phase of V_{td}, and is constrained to lie between 8° and 32° corresponding to $\sin 2\beta$ between 0.3 and 0.9. Thus a magnitude clearly below 0.3 or a negative value of $\sin 2\widetilde{\beta}$ would indicate new physics.

To proceed we assume that measurements yield $\sin 2\widetilde{\beta}$ between 0.4 and 0.8 corresponding in the standard model to a value

$$\widetilde{\beta}=\widetilde{\beta}_1=12°\ \text{to}\ 27°.$$

There exists the possibility that the true value of $\widetilde{\beta}$ is

$$\widetilde{\beta}_2=\frac{\pi}{2}-\widetilde{\beta}_1,\quad =78°\ \text{to}\ 63°. \tag{1a}$$

This would mean a large new physics contribution that reverses the sign of Re M_{12}. Within the standard phase convention this new physics contribution could be approximately CP invariant. As we now proceed to show this large new physics effect is not easy to detect.

The next goal of B factories is the measurement of $\sin 2(\widetilde{\beta}+\gamma)$ from the asymmetry in decays like $B^0\to\pi^+\pi^-$. For the moment we neglect the penguin problem and assume this is measured. In the standard model there is almost no constraint [3] on the possible value of $\sin 2(\widetilde{\beta}+\gamma)$ for a value of $\sin 2\widetilde{\beta}$ in the range we have assumed. Within the standard model there will in general be only one set of angles $(\widetilde{\beta}_1,\gamma_1)$ consistent with these two measurements, although in general there is an eight-fold ambiguity [4]. In particular, corresponding to the choice $\widetilde{\beta}=\widetilde{\beta}_2$ there is a corresponding choice

$$\gamma_2=\pi-\gamma_1. \tag{1b}$$

Since the allowable values of γ, which are independent of B-$\overline{B}$ mixing and in our scenario are unchanged by the new physics, are approximately symmetric with respect to 90° the choice γ_2 is always allowable. A number of experiments are directed at determining $\sin\gamma$; this does not distinguish γ_1 from γ_2.

If γ_1 is far from 90° corresponding to $|\rho|\geqslant 0.2$ then γ_2 is distinguished from γ_1 by the sign of ρ and thus by the magnitude of V_{td}. The best prospect for determining this is from the rate [5] of $K^+\to\pi^+\nu\overline{\nu}$ which is approximately proportional to

$$[(1\pm 0.15)+(2\pm 0.25)(1-\rho-i\eta)]^2$$

where the first conservative error is due to the charm contribution and the second to uncertainty in m_t and V_{cb}. For $|\rho|=0.2$ the difference between the two signs of ρ is almost a factor of 2 in the $K^+\to\pi^+\nu\overline{\nu}$ rate.

Another possibility is to look for interfering amplitudes that can be used to determine $\cos\gamma$. An example is the penguin-tree interference in the decay $B^0\to\pi^-K^+$. In contrast one expects that the decay $B^+\to\pi^+K^0$ is a pure penguin diagram. One then finds [6]

$$R=\frac{\Gamma(B^0\to\pi^-K^+)}{\Gamma(B^+\to\pi^+K^0)}=1-2r\cos\gamma+r^2 \qquad (2)$$

where r is the ratio of tree to penguin diagrams. If we accept the sign of r as given by factorization and note that we expect $|r|\leqslant\frac{1}{3}$ then the sign of $(1-R)$ gives the sign of $\cos\gamma$ which can distinguish γ_1 from γ_2.

However, if $\cos\gamma$ is close to zero, corresponding to ρ close to zero, which is in the center of the allowed (ρ,η) region, then neither of the above methods can distinguish the solutions in Eq. (1b) from the standard model.

Instead of relying on γ one can try to find a method of distinguishing $\widetilde{\beta}_1$ from $\widetilde{\beta}_2$. Grossman and Quinn [4] suggest comparing the asymmetry in the decay $B\to D^+D^-$ to that of $B\to\psi K_S$. Including a penguin contribution to the D^+D^- decay they find

$$a(D^+D^-)=\sin 2\widetilde{\beta}-2r\cos 2\widetilde{\beta}\sin\widetilde{\beta}\cos\delta \qquad (3)$$

where r is the penguin to tree amplitude ratio and δ is the strong phase difference between penguin and tree diagrams. If one assumes $r<0$ from factorization and $\cos\delta>0$ then if $\widetilde{\beta}=\widetilde{\beta}_1$ the asymmetry is increased due to the penguin diagram whereas if $\widetilde{\beta}=\widetilde{\beta}_2$ the asymmetry is decreased.

Actually if $\widetilde{\beta}=\widetilde{\beta}_2$ Eq. (3) is not correct since it assumes that the phase of the penguin amplitude, given by the phase β of V_{td}, equals $\widetilde{\beta}$. However in the scenario we consider while $\widetilde{\beta}$ is given by Eq. (1a), the phase β is constrained to lie between 12° and 27°. In this case Eq. (3) becomes, to first order in r,

$$a(D^+D^-)=\sin 2\widetilde{\beta}_2-2r\cos 2\widetilde{\beta}_2\sin\beta\cos\delta. \qquad (4)$$

The previous conclusion that if $r<0$ the asymmetry is decreased by the penguin diagram if $\widetilde{\beta}=\widetilde{\beta}_2$ still holds.

Another way to directly distinguish $\widetilde{\beta}_2$ from $\widetilde{\beta}_1$ in this scenario involves decays dominated by the $b\to d$ penguin graph. Assuming t dominance the asymmetry of a decay like $B_d\to K^0\overline{K^0}$ is given by $\sin 2(\widetilde{\beta}-\beta)$. If we assume $\widetilde{\beta}$ is around 70°, corresponding to typical $\widetilde{\beta}_2$ value then any allowable value of β gives an asymmetry greater than 0.9. In contrast in the standard model $\widetilde{\beta}=\beta$ and the asymmetry vanishes. Fleischer [7] has pointed out that there may be significant contributions from u and c quarks such that the standard model value may not be zero. Nevertheless a very large asymmetry of 80% or greater would be strong evidence for new physics. While the branching ratio is small not so many events are needed just to show that the asymmetry is very large.

We turn now to the B_s system. The first quantity of interest that can be measured is x_s. The ratio x_d/x_s is given in the standard model (SM) by

$$\frac{x_d}{x_s}=\lambda^2[(1-\rho)^2+\eta^2]K \qquad (5)$$

where K is the ratio of $B_B\eta_2 f_B^2$ for the B_d as compared to B_s. In the SU(3) limit $K=1$ and estimates from lattice and other calculations give K between 0.7 and 0.9. Thus the measurement of x_s can be used to put a constraint on (ρ,η), primarily on ρ. In fact the present limit on x_s disfavors values $\rho<-0.2$. A small value of x_s leads to a significant negative value of ρ and a large value of x_s to a positive value ρ. If this is inconsistent with the value of (ρ,η) determined from the asymmetry measurements it could be a sign of new physics in B_d-$\overline{B_d}$ mixing. Note that this new physics in general would cause $\widetilde{\beta}$ to be different from β and change the value of x_d invalidating Eq. (5). However, the larger new contribution to B_d-$\overline{B_d}$ mixing implied by Eq. (1a) could not be demonstrated in this way.

It would also be possible to compare the values of (ρ,η), mainly $(1-\rho)$, that fits x_s/x_d with that from $K^+\to\pi^+\nu\overline{\nu}$. If these are inconsistent it would be probably a sign of a new physics contribution to x_d.

If Δm_s is not too large one can study the CP-violating asymmetries from the $\sin(\Delta m_s t)$ term in tagged B_s decays. For decays such as $B_s\to\psi\eta$ the asymmetry is given by $\sin\theta_s$ where $\theta_s=2\lambda^2\eta$ which is between 0.02 and 0.05. If the asymmetry is significantly larger that would be a sign of new physics in B_s-$\overline{B_s}$ mixing. For decays governed by $b\to u\overline{u}d$, such as $B_s\to\rho^0K_S$, the asymmetry in the tree approximation is $\sin(\theta_s+2\gamma)$. If θ_s is consistent with zero this gives $\sin 2\gamma$, the sign of which distinguishes γ_2 from γ_1. There is likely a sizable penguin contribution to $B_s\to\rho^0K_S$, but the fact that one wants only the sign of $\sin 2\gamma$ may make this useful in spite of the penguin.

In analyzing prospective B asymmetry experiments it is natural and appropriate to assume the standard model and see how well these can constrain the parameters (ρ,η). The purpose of the present note is to emphasize that it is also important to look at new physics effects and see whether or not a given set of experiments can detect them.

In particular we have looked at one particular ambiguity given by Eqs. (1), which implies large new physics effects which may prove very difficult to detect. Proposed experiments should be analyzed from the point of view of resolving such ambiguities.

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