

CP Violation Due To New $\Delta B = 1$ Amplitudes

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We make a systematic analysis of the effects of new physics in the B decay amplitudes on the CP asymmetries in neutral B decays. Although these are expected to be smaller than new physics effects on the mixing amplitude, they are easier to probe in some cases. The effects of new contributions to the mixing amplitude are felt universally across all decay modes, whereas the effects of new decay amplitudes could vary from mode to mode. In particular the prediction that the CP asymmetries in the B decay modes with $b \rightarrow c\bar{c}s$, $b \rightarrow c\bar{c}d$, $b \rightarrow c\bar{u}d$ and $b \rightarrow s\bar{s}s$ should all measure the same quantity ($\sin 2\beta$ in the Standard Model) could be violated.

1 Introduction

In the limit of one dominant decay amplitude, the CP violating asymmetries measured in the time dependent decays of neutral B mesons to CP eigenstates depend only on the sum of the phase of the $B^0 - \bar{B}^0$ mixing amplitude and the phase of the decay amplitude.¹ The size of these phases, however, is at present very much uncertain. Thus, the currently allowed range for the CP asymmetries measurements in B decays is very large. Yet, there exists a precise prediction concerning the CP asymmetries in B decays made by the Standard Model:²

- The CP asymmetries in all B decays that do not involve direct $b \rightarrow u$ (or $b \rightarrow d$) transitions have to be the same.

New physics could in principle contribute to both the mixing matrix and to the decay amplitudes. The distinguishing feature of new physics in mixing matrices is that its effect is universal, *i.e.*, although it changes the magnitude of the asymmetries it does not change the patterns predicted by the Standard Model. In particular, the above prediction is not violated. Thus, the best way to search for these effects would be to compare the observed CP asymmetry in a particular decay mode with the asymmetry predicted in the Standard Model. However, due to the uncertainties in the Standard Model predictions these effects have to be large, and even then may be hard to detect.³

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In contrast, the effects of new physics in decay amplitudes are manifestly non-universal, *i.e.*, they depend on the specific process and decay channel under consideration. Experiments on different decay modes that would measure the same CP violating quantity in the absence of new contributions to decay amplitudes, measure in this case different CP violating quantities. Thus, the above mentioned prediction can be violated.²

2 The Effects of New Decay Amplitudes

Consider B decay into CP eigenstates where the decay amplitude A contains contributions from two terms with magnitudes A_i , CP violating phases ϕ_i and CP conserving phases δ_i (in what follows it will be convenient to think of A_1 giving the dominant Standard Model contribution, and A_2 giving the sub leading Standard Model contribution or the new physics contribution)

$$A = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2}, \quad \bar{A} = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2}. \quad (1)$$

To first order in $r \equiv A_2/A_1$ the time dependent CP asymmetry for the decays of states that were tagged as pure B^0 or \bar{B}^0 at production into CP eigenstates is given by⁴

$$a_f(t) = a_f^{\cos} \cos(\Delta Mt) + a_f^{\sin} \sin(\Delta Mt), \quad (2)$$

with

$$\begin{aligned} a_f^{\cos} &= -2r \sin(\phi_{12}) \sin(\delta_{12}), \\ a_f^{\sin} &= \sin 2(\phi_M + \phi_1) + 2r \cos 2(\phi_M + \phi_1) \sin(\phi_{12}) \cos(\delta_{12}), \end{aligned} \quad (3)$$

and we have defined $\phi_{12} = \phi_1 - \phi_2$ and $\delta_{12} = \delta_1 - \delta_2$.

In the case $r = 0$ or $\phi_{12} = 0$ one recovers the frequently studied case where $a_f^{\cos} = 0$ and $a_f^{\sin} = -\sin 2(\phi_M + \phi_1)$. In decay modes where the above condition holds (to a good approximation) in the Standard Model, one is sensitive to new physics if it results in $r \neq 0$ and $\phi_{12} \neq 0$. There are several ways one can look for this kind of new physics *e.g.*:

(a) Direct CP violation. This occurs when $\delta_{12} \neq 0$ and can be measured by a careful study of the time dependence since it gives rise to $a_f^{\cos} \neq 0$. Such a scenario would also give rise to CP asymmetries in charged B decays. While this would be a clear signal of new physics in the decay amplitude, the opposite is not true. In cases where the relative strong phase between the new physics and the Standard Model amplitudes vanishes, the Standard Model predictions continue to hold.

(b) Different quark level decay channels that measure the same phase when only one amplitude contributes, now measure different phases if more than

one amplitude contributes, *i.e.* two different processes with the same ϕ_1 , but with different r or ϕ_2 . This does not depend on new strong phases, and we concentrate on this.

To this end we write

$$a_f^{\text{sin}} = -\sin 2(\phi_0 + \delta\phi), \quad (4)$$

where ϕ_0 is the phase predicted at leading order in the Standard Model, and $\delta\phi$ is the correction to it. The cleanest Standard Model predictions are found in the modes that measure β when $r = 0$, and we concentrate on these. These are $b \rightarrow c\bar{c}s$ (*e.g.* $B \rightarrow \psi K_S$), $b \rightarrow c\bar{c}d$ (*e.g.* $B \rightarrow D^+ D^-$), $b \rightarrow c\bar{u}d$ (*e.g.* $B \rightarrow D_{CP}\rho$) and $b \rightarrow s\bar{s}s$,⁵ (*e.g.* $B \rightarrow \phi K_S$). We now estimate the size of the sub-leading Standard Model corrections to the above processes, which then allows us to quantify how large the new physics effects have to be in order for them to be probed.

There is a Standard Model penguin contribution to $B \rightarrow \psi K_S$. However, as is well known, this contribution has the same phase as the tree level contribution and hence $\delta\phi_{SM} = 0$ in Eq. (4). The mode $b \rightarrow c\bar{c}d$ also has a penguin correction in the Standard Model. However, in this case $\phi_{12} = \mathcal{O}(1)$ and we estimate the correction as

$$\delta\phi_{SM}(B \rightarrow D^+ D^-) \simeq \frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*} \frac{\alpha_s(m_b)}{12\pi} \log(m_b^2/m_t^2) \lesssim 0.1, \quad (5)$$

where the upper bound is obtained for $|V_{td}| < 0.02$, $m_t = 180$ GeV and $\alpha_s(m_b) = 0.2$. Recent estimates⁶ found that an even larger value of up to $\delta\phi_{SM} \sim 0.3$ cannot be excluded. The mode $b \rightarrow c\bar{u}d$ does not get penguin corrections, however there is a doubly Cabbibo suppressed tree level correction coming from $b \rightarrow u\bar{c}d$. Thus $B \rightarrow D_{CP}\rho$ gets a second contribution with different CKM elements. We estimate

$$\delta\phi_{SM}(B \rightarrow D_{CP}\rho) = \frac{V_{ub}V_{cd}^*}{V_{cb}V_{ud}^*} r_{FA} \leq 0.05. \quad (6)$$

where r_{FA} is the ratio of matrix elements with $r_{FA} = 1$ in the factorization approximation. We have used $|V_{ub}/V_{cb}| < 0.11$, and what we believe is a reasonable limit for the matrix elements ratio, $r_{FA} < 2$, to obtain the upper bound.

For the neutral current modes $B \rightarrow \phi K_S$ we use CKM unitarity to write the decay amplitude as a sum of two terms⁷

$$A = V_{cb}V_{cs}^* A^{ccs} + V_{ub}V_{us}^* A^{uus}. \quad (7)$$

Table 1: Summary of the useful modes. The “SM angle” entry corresponds to the angle obtained assuming one decay amplitude. New contributions to the mixing amplitude would shift all the entries by δ_{m_d} . $\delta\phi$ (defined in Eq. (4)) corresponds to the (absolute value of the) correction to the universality prediction within each model: $\delta\phi_{SM}$ – Standard Model, $\delta\phi_A$ – Effective Supersymmetry, $\delta\phi_B$ – Models with Enhanced Chromomagnetic Dipole Operators and $\delta\phi_C$ – Supersymmetry without R-parity. 1 means that the phase can get any value.

Mode	SM angle (ϕ_0)	$\delta\phi_{SM}$	$\delta\phi_A$	$\delta\phi_B$	$\delta\phi_C$	BR
$B \rightarrow \psi K_S$	β	0	0.1	0.1	0.1	7×10^{-4}
$B \rightarrow D^+ D^-$	β	0.1	0.2	0.6	0.6	4×10^{-4}
$B \rightarrow D_{CP}\rho$	β	0.05	0	0	0.5	10^{-5}
$B \rightarrow \phi K_S$	β	0.05	1	1	0	10^{-5}

The correction due to the second term is doubly Cabbibo suppressed. Assuming that ϕ is a pure $s\bar{s}$ state and for a very heavy b quark $A^{uus}/A^{ccs} = 1$. A^{uus} may be enhanced due to the finite b mass, or due to $SU(3)_{flavor}$ mixing since the ϕ also contains a small $u\bar{u}$ component. The first effect is unlikely to be large, and the second is experimentally known to be small. Thus, we believe that a reasonable limit for the matrix elements ratio is $A^{uus}/A^{ccs} < 2$, leading to

$$\delta\phi_{SM}(b \rightarrow s\bar{s}s) \leq 0.05. \quad (8)$$

We emphasize the importance of the decay $B \rightarrow \phi K_S$ in probing new physics. Since this is a penguin mediated decay in the Standard Model, it is the most sensitive of all the modes we addressed to the possible contributions from new physics. Moreover, although technically classified as a “rare decay” the CP asymmetry in this mode is possibly measurable at the early stages of the B factories. This is because the recent CLEO measurements of the $B \rightarrow \pi K'$ and $B \rightarrow \eta' K$ branching ratios suggest that penguin induced decays are large, and one can then estimate $BR(B_D \rightarrow \phi K_S) \sim 10^{-5}$. An important advantage is that the efficiency for tagging this mode is very large. One can reconstruct the ϕ using the decay $\phi \rightarrow K^+ K^-$ which has a large branching ratio $\sim 50\%$ and very high efficiency (probably up to 80–90%). The other two dominant decay modes $\phi \rightarrow K_L K_S$ and $\phi \rightarrow \pi\rho$ can also be used (probably with smaller efficiency.) Thus, the effective rate for $B \rightarrow \phi K_S$ is within a factor of ten of $B \rightarrow \psi K_S$ and of the same order as $B \rightarrow \pi^+ \pi^-$.

We have studied three models:² (a) Effective Supersymmetry, (b) Models with enhanced Chromomagnetic dipole operators, and (c) Supersymmetry without R parity. In Table 1 we show the largest allowable effects in these models. Such effects in general supersymmetric models were also studied.⁸ In

all of the examples one finds that large experimentally detectable effects are possible.

3 Conclusions

CP asymmetries in B decays can be a very useful tool in looking for physics beyond the Standard Model. One can look for new contributions to the $B - \bar{B}$ mixing. However, these have to be large to be discovered. Alternatively, new contributions to the B decay amplitudes can be discovered even if they are rather small, $O(5\%)$. With a large strong phase, this new contribution can lead to sizeable direct CP violation. Even without it, such effects can be probed by comparing two experiments that measure the same phase ϕ_0 in the Standard Model [see Eq. (4)]. The most promising way to look for new physics effects in decay amplitudes is to compare all the B decay modes that measure β in the Standard Model. The best mode is $B \rightarrow \psi K_S$ which has a sizeable rate and negligible theoretical uncertainty. This mode should be the reference mode to which all other measurements are compared. The $b \rightarrow c\bar{u}d$ and $b \rightarrow s\bar{s}s$ modes are also theoretically very clean. Thus, the two “gold plated” relations are

$$|\phi(B \rightarrow \psi K_S) - \phi(B \rightarrow \phi K_S)| < 0.05, \quad (9)$$

and

$$|\phi(B \rightarrow \psi K_S) - \phi(B \rightarrow D_{CP})| < 0.05. \quad (10)$$

Any deviation from these two relations will be a clear indication for new physics in decay amplitudes. The mode $B \rightarrow \phi K_S$ is particularly sensitive to new physics since it is a loop induced rare decay in the Standard Model.

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