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Fast CP Violation*

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Abstract

B flavor tagging will be extensively studied at the asymmetric B factories due to its importance in CP asymmetry measurements. The primary tagging modes are the semileptonic decays of the b (lepton tag), or the hadronic $b \to c(\to s)$ decays (kaon tag). We suggest that looking for time dependent CP asymmetries in events where one B is tagged leptonically and the other one is tagged with a kaon could result in an early detection of CP violation. Although in the Standard Model these asymmetries are expected to be small, $\sim 1\%$, they could be measured with about the same amount of data as in the "gold-plated" decay $B_d \to \psi K_S$. In the presence of physics beyond the Standard Model, these asymmetries could be as large as $\sim 10\%$, and the first CP violation signal in the B system may show up in these events. We give explicit examples of new physics scenarios where this occurs.

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I. INTRODUCTION

One of the goals of the asymmetric B factories is to study CP violation in B meson decays. CP violation has not been observed outside the kaon system, thus it is important to identify B decay modes that would allow an early detection of this phenomenon. The CP asymmetry in the $B_d \to \psi K_S$ decay is the benchmark to which all other CP asymmetry measurements at the B factories are usually compared [1]. The branching ratio is relatively large (5×10^{-4}) and the ψ is easy to reconstruct from its decay into two leptons. In addition, the CP asymmetry is expected to be $\mathcal{O}(1)$ in the Standard Model, and allow a clean measurement of the CKM angle β. It is also commonly assumed that this is the mode in which CP violation will first be observed at the asymmetric B factories.

A crucial ingredient in the CP asymmetry measurements is flavor tagging. In the asymmetric B factories there are two main tagging techniques [2]. The first is the "lepton tag", where the flavor is determined by the lepton charge in a semileptonic B decay. The second, the "kaon tag", uses hadronic B_d decays to final states with $\Delta C = \pm 1$, namely decays with one charmed hadron in the final state. These further decay into a final state that contains only one kaon, whose charge identifies the original B meson flavor.

In this work we propose that CP asymmetries in events where both B's are flavor tagged are also excellent candidates for an early observation of CP violation. The cases where both B's are tagged leptonically or both with kaons result in CP asymmetries that are proportional only to CP violation in the $B^0 - \bar{B}^0$ mixing amplitude and, in particular, they vanish in the limit where the neutral B width difference, $\Delta\Gamma$, is zero. The case we concentrate on here is where one of the B's is tagged leptonically and the other using the kaon tag. This can lead to CP violation due to interference between the neutral B mixing and decay amplitudes. Theoretically, these are given by the CP asymmetries in hadronic semi-inclusive B_d decays to final states with $\Delta C = \pm 1$. Due to the importance of the kaon tag to the B factories program, the experimental issues regarding the detection of these final states will be extensively studied before and after the B factories turn on. Moreover, the search for these states should not result in much additional effort since it will be carried out when performing the tagging. Thus, we believe that the possibility of an early detection of CP violation in these modes requires a simple extension of the flavor tagging studies.

The CP asymmetries we consider are the following:

$$a_{\Delta C=1}(t) \equiv \frac{N_{B_\ell \bar{B}_K}(t) - N_{\bar{B}_\ell B_K}(t)}{N_{B_\ell \bar{B}_K}(t) + N_{\bar{B}_\ell B_K}(t)}, \tag{1.1}$$

$$a_{\Delta C=-1}(t) \equiv \frac{N_{B_\ell B_K}(t) - N_{\bar{B}_\ell \bar{B}_K}(t)}{N_{B_\ell B_K}(t) + N_{\bar{B}_\ell \bar{B}_K}(t)}, \tag{1.2}$$

$$a_{|\Delta C|=1}(t) \equiv \frac{(N_{B_\ell B_K} + N_{B_\ell \bar{B}_K})(t) - (N_{\bar{B}_\ell B_K} + N_{\bar{B}_\ell \bar{B}_K})(t)}{(N_{B_\ell B_K} + N_{B_\ell \bar{B}_K})(t) + (N_{\bar{B}_\ell B_K} + N_{\bar{B}_\ell \bar{B}_K})(t)}. \tag{1.3}$$

In the above notation $N_{B_\ell \bar{B}_K}$ is the number of events where a B has been tagged leptonically and a $\bar{B}$ has been tagged with a kaon ($N_{B_\ell B_K}$ and $N_{\bar{B}_\ell \bar{B}_K}$ are similarly defined). As we will show, in the Standard Model, the number of $B^0 - \bar{B}^0$ pairs required to get a statistically significant CP violation signal in $B_d \to \Delta C = \pm 1$ is expected to be larger than that required in $B_d \to \psi K_S$, yet achievable in approximately one year of data taking at nominal luminosity. If, however, there is physics beyond the Standard Model, it could lead to the possibility of observing CP violation in $B_d \to \Delta C = \pm 1$ in the very early stages of data taking, with over an order of magnitude fewer $B^0 - \bar{B}^0$ events than those needed for the CP asymmetry in $B_d \to \psi K_S$.

II. FORMALISM AND STANDARD MODEL EXPECTATIONS

The suggestion of looking for a CP asymmetry in the semi-inclusive $B_d \to \Delta C = \pm 1$ modes, the formalism to calculate it, as well as the Standard Model expectations were presented in a recent paper by Beneke, Buchalla and Dunietz [3]. Ignoring the width difference of the neutral B mesons ($\Delta\Gamma/\Delta m \simeq 0$), one obtains

$$a^{SM}_{\Delta C=\pm 1}(t) = \mathcal{C} \times \frac{\mathrm{Im}\,\lambda_{SM} \sin \Delta m t}{(1 \mp \cos \Delta m t) + |\lambda_{SM}|^2 (1 \pm \cos \Delta m t)}, \tag{2.1}$$

and

$$a^{SM}_{|\Delta C|=1}(t) \simeq \mathcal{C} \times 2\mathrm{Im}\,\lambda_{SM} \sin \Delta m t, \tag{2.2}$$

where $\lambda_{SM} = e^{i2\beta}(V^*_{ub}V_{cd})/(V^*_{cb}V_{ud})$ and $\mathcal{C}$ is a dilution factor that arises because one is summing over several exclusive modes, possibly with opposite CP asymmetries. Assuming local quark-hadron duality, setting all bag factors equal to one, and using $f_B = 180$ MeV, $m_b = 4.8$ GeV and $m_c = 1.4$ GeV, one finds $\mathcal{C} = -0.21$ [3]. Using $|V_{ub}|/|V_{cb}| = 0.1$ one then obtains

$$a^{SM}_{\Delta C=\pm 1}(t) \simeq \frac{-0.005 \sin(\alpha-\beta) \sin \Delta m t}{(1 \mp \cos \Delta m t) + 0.0005(1 \pm \cos \Delta m t)} \tag{2.3}$$

and

$$a^{SM}_{|\Delta C|=1}(t) \simeq -0.01\, \sin(\alpha - \beta) \sin \Delta m t. \tag{2.4}$$

For comparison, the CP asymmetry in $B_d \to \psi K_S$ is given by

$$a^{SM}_{\psi K_S}(t) = \sin(2\beta) \sin \Delta m t, \tag{2.5}$$

with essentially no uncertainty. We consider the value of $\mathcal{C}$ used above only as a reasonable estimate due to the large uncertainties in some of the factors that go into its determination. Until these are better known, the CP asymmetries in Eqs. (2.3) and (2.4) are unlikely to be of much use in obtaining precise measurements of CKM angles, as suggested in [3]. The importance of these modes lies, rather, in the fact that they may lead to an early detection of CP violation; possibly the first at the B factories.

The number of $B^0 - \bar{B}^0$ events needed to establish CP violation depends not only on the expected CP asymmetry, but also on the B meson branching ratio as well as on tagging and detection efficiencies for that particular final state. Thus, the small CP asymmetry in $B_d \to \Delta C = \pm 1$ is compensated for by the large branching ratio into these modes. We can estimate the number of $B^0 - \bar{B}^0$ pairs (N_f) required to obtain a 3σ CP violation signal in a given final state f using

$$N_f \epsilon_f \mathrm{BR}_f \gtrsim \frac{10}{a_f^2}, \tag{2.6}$$

where ϵ_f is the combination of detection and B flavor tagging efficiencies, BR_f the branching ratio, and a_f is a time integrated CP asymmetry for the final state f. We present below the results based on Eq. (2.6) for the various modes, relegating details concerning its implementation to the Appendix.

For the $\Delta C = \pm 1$ modes we find in the Standard Model,

$$\begin{aligned} N_{|\Delta C|=1} &\gtrsim \frac{1 \times 10^7}{\sin^2(\beta - \alpha)}, \\ N_{\Delta C=+1} &\gtrsim \frac{1 \times 10^7}{\sin^2(\beta - \alpha)}, \\ N_{\Delta C=-1} &\gtrsim \frac{3 \times 10^7}{\sin^2(\beta - \alpha)}. \end{aligned} \tag{2.7}$$

For comparison, the number of $B^0 - \bar{B}^0$ pairs needed to establish a CP violation in $B_d \to \psi K_S$ can be estimated to be about

$$N_{\psi K_S} \gtrsim \frac{1.5 \times 10^6}{\sin^2(2\beta)} \tag{2.8}$$

Thus, one can expect to observe CP violation in the $B_d \to \Delta C = \pm 1$ modes with roughly an order of magnitude more data than that needed in the "gold-plated" $B_d \to \psi K_S$ mode. This amount of data will be available after one to two years of data taking with the expected luminosity yielding $\sim 10^7$ $B^0 - \bar{B}^0$ pairs per year. If it turns out that $|\mathcal{C}| > 0.21$ or if $|\sin(\alpha - \beta)| > |\sin(2\beta)|$, it may be possible to observe CP violation in the $B_d \to \Delta C = \pm 1$ modes with a comparable amount of data as in $B_d \to \psi K_S$ even in the Standard Model. Given the fact that, in any case, data will be taken and analyzed in the $B_d \to \Delta C = \pm 1$ modes, it is important then to also search for CP violation.

III. NEW PHYSICS

The situation gets even more interesting in the presence of physics beyond the Standard Model. Note from Eq. (2.6) that N_f scales as $(a_f)^{-2}$, and that the small value of $(a_{\Delta C = \pm 1})$ in Eqs. (2.3) and (2.4) is essentially due to the small ratio of amplitudes,

$$\left|\frac{A(b\to u\bar{c}d)}{A(b\to c\bar{u}d)}\right|_{SM} = \lambda\left|\frac{V_{ub}}{V_{cb}}\right|. \tag{3.1}$$

However, the $b\to u\bar{c}d$ rate is not well measured at present and allows for large CP violating new physics contributions. If such new contributions significantly enhance the magnitude of that amplitude, they will also enhance the CP asymmetries in these modes.

Let us first present a model independent analysis of the bounds on physics beyond the Standard Model for the $b\to u\bar{c}d$ transition. We parameterize the new physics effects by the quantity

$$r \equiv \frac{A(b\to u\bar{c}d)_{NP}}{A(b\to u\bar{c}d)_{SM}}. \tag{3.2}$$

In the limit $|r|\gg 1$, Eqs. (2.3) and (2.4) become[a]

$$a_{\Delta C=\pm 1}(t) \simeq \frac{-|r|\;0.005\sin(2\beta+\theta)\sin\Delta m t}{(1\mp\cos\Delta m t)+0.0005|r|^2(1\pm\cos\Delta m t)}, \tag{3.3}$$

and

$$a_{|\Delta C|=1}(t) \simeq -0.01|r|\sin(2\beta+\theta)\sin\Delta m t, \tag{3.4}$$

respectively, where θ is the phase between $A(b\to u\bar{c}d)_{NP}$ and $A(b\to c\bar{u}d)_{SM}$. Thus, we see that for $r\gtrsim 10$ the CP asymmetry can be enhanced by a factor of 10, and hence a CP violation signal can be obtained with a factor 100 less data than required in the Standard Model. Note that since we care only about order of magnitude estimates, we have ignored corrections associated with generalizing the results of [3] to account for operators with non-standard Lorentz structures. Moreover, we have set $\Delta\Gamma=0$. Although this is a very good approximation in the Standard Model, this may not be the case with new physics since $\Delta\Gamma$ is generated by final states that are common to both B and $\bar{B}$, and a large new contribution

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[a] We ignore new physics contributions to $B^0-\bar{B}^0$ mixing and $b\to c\bar{u}d$ decay since they cannot significantly enhance the CP asymmetry in $B_d\to\Delta C=\pm 1$. See Refs. [4] and [5], respectively, for a discussion on detecting such contributions using CP violating B decays.

to the $b \to u\bar{c}d$ decay could enhance it. In general, this results in a higher sensitivity to CP violation.

If the new physics consists of right-handed currents then the only relevant bound on operators producing $b \to u\bar{c}d$ comes from this process itself. There are no reported bounds on either the inclusive or exclusive decays. In order to derive such a constraint, we require that the branching ratio for this mode should not be large enough to have a significant effect on the B semi-leptonic branching ratio. This implies $\mathrm{BR}(b \to u\bar{c}d) \lesssim 10\%$. Comparing to the Standard Model expectation $\mathrm{BR}(b \to u\bar{c}d)_{SM} \sim 1 \times 10^{-4}$ we obtain that $r \lesssim 30$.[b] In particular, $r \sim 10$ would lead to $\mathrm{BR}(b \to u\bar{c}d) \sim 1\%$, which certainly cannot be excluded by current data.

Considerations of exclusive decays also lead to similar bounds. For example, $r \sim 10$ combined with $\mathrm{BR}(B^+ \to \bar{D}^0\rho^+) \sim 0.5\%$ leads to $\mathrm{BR}(B^+ \to D^0\pi^+) \simeq 1.2 \times 10^{-4}$. Although CLEO has no bounds on this process, it is likely that a dedicated search could obtain a bound $\mathrm{BR}(B^+ \to D^0\pi^+) \sim 10^{-4}$. A larger enhancement up to $\mathrm{BR}(B^+ \to D^0\pi^+) \sim 10^{-3}$ is unlikely, as this might result in intrinsic inconsistencies in other measurements such as $B \to DK$ [7]. In conclusion, we believe that a value of r as big as 10 is allowed by all current data.

As a simple example of a new physics scenario that can lead to such large values of r, and thus enhanced CP violation in $B_d \to \Delta C = \pm 1$, we consider a non minimal Left-Right Symmetric Model [8]. Namely, one where the left (V^L) and right (V^R) quark mixing matrices are not related. We assume identical gauge couplings, $g_L = g_R$, and that the $W_L - W_R$ mixing is negligible. Then, tree level W_R exchange can lead to the desired final state. The ratio of the new amplitude to the Standard Model one is

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[b]Note that such a large new contribution to the $b \to u\bar{c}d$ decay could even help reconcile the differences between the theoretical prediction and the results of the B semi-leptonic branching ratio and charm counting experiments [6].

$$|r| \approx \left| \frac{V^R_{ub} V^R_{cd}}{V^L_{ub} V^L_{cd}} \right| \left(\frac{m^2_{W_L}}{m^2_{W_R}} \right) . \tag{3.5}$$

For $|V^R_{ub} V^R_{cd}| \simeq 1$ and $m_{W_R} \simeq 10\, m_{W_L}$ we get $r \simeq 10$, while still satisfying all other constraints on the model. Of course, we also assume that the CP violating phase in V^R is large, $O(1)$.

In this case the CP asymmetry is enhanced compared to its Standard Model value by about a factor of 10, namely, it can reach the 10% level. As a consequence, we would observe a CP violation signal very fast, with about 10^5 $B^0 - \bar{B}^0$ pairs. Moreover, such enhanced CP violation would be a clear signal of physics beyond the Standard Model. Of course, if no such signal is found, we will be able to put bounds on the magnitude of new contributions to the $b \to u\bar{c}d$ amplitude.

We have also studied other scenarios, *e.g.*, models with extra charged scalars, models with diquarks, supersymmetry with four generations and broken R parity, all of which allow $r \sim 10$, and hence the possibility of an early detection of CP violation in $B_d \to \Delta C = \pm 1$.

IV. CONCLUSIONS

We have proposed that it is important to search for CP violation in events where one B has been tagged leptonically, and the other B by a kaon. Within the Standard Model, the number of $B^0 - \bar{B}^0$ events required to detect CP violation in this mode could be similar to that for $B_d \to \psi K_S$, and could be obtained in the first year of running at the B factories. In the presence of new physics, it is possible that CP violation could be detected in $B_d \to \Delta C = \pm 1$ with significantly less data than needed to detect it in $B_d \to \psi K_S$, and thus be the first CP violating signal at the asymmetric B factories. Moreover, new physics could also contribute to the neutral B width difference, resulting in observable CP violation also in the modes where both B's are tagged either leptonically, or with kaons. Given the fact that B flavor tagging will be intensively studied, we suggest that the possibility of observing CP violation in these modes should be seriously considered.

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APPENDIX A: NUMERICAL ESTIMATES

The number of $B^0 - \bar{B}^0$ pairs required to obtain a statistically significant observation of CP violation has been estimated in the text by means of

$$N_f \epsilon_f \mathrm{BR}_f \gtrsim \frac{10}{a_f^2} \tag{A1}$$

where, given a time interval (a, b), we have defined the CP asymmetry

$$a_f = \frac{\int_a^b \mathcal{N}_f(t)\, dt}{\int_a^b \mathcal{D}_f(t)\, dt}, \tag{A2}$$

with

$$\begin{aligned} \mathcal{N}_f(t) &= \Gamma(B(t) \to f) - \Gamma(\bar{B}(t) \to \bar{f}), \\ \mathcal{D}_f(t) &= \Gamma(B(t) \to f) + \Gamma(\bar{B}(t) \to \bar{f}). \end{aligned} \tag{A3}$$

Moreover, the number of neutral B decays are an oscillatory function of time, and hence we use

$$\mathrm{BR}_f = \frac{\int_a^b \mathcal{D}_f(t)\, dt}{\Gamma} \tag{A4}$$

where Γ is the total B width, finally leading to

$$N_f \gtrsim \frac{10\,\Gamma}{\epsilon_f} \frac{\int_a^b \mathcal{D}_f(t)\, dt}{\left(\int_a^b \mathcal{N}_f(t)\, dt\right)^2}. \tag{A5}$$

Here we are assuming that we have already reconstructed the time information of the decay, since otherwise we could not make the $\int_a^b$ integral. Although in practise the CP violating signal is best extracted by using all the data to perform a maximal likelihood fit to Eqs.

(2.1) and (2.2), or their generalizations in the case of physics beyond the Standard Model, we believe that the above equation yields a reasonable estimate of the number of $B^0 - \bar{B}^0$ pairs required to see a CP violating signal.

Using the information in the BABAR Technical Design Report, and recent studies made for the BABAR physics book [2], we estimate $\epsilon_{\Delta C=1} \approx 2.5 \times 10^{-2}$ for all the $\Delta C = 1$ modes. This estimate is a product of 10% for the lepton tag, 50% for the kaon tag and a further 50% due to the fact that in the inclusive decay one needs to identify both the flavor and the charge of the decaying B. Similarly, we estimate $\epsilon_{\psi K_S} \approx 1.5 \times 10^{-2}$ as a product of 30% for the combined lepton and kaon tags, 10% for the ψ reconstruction, and 50% for the K_S reconstruction. We have ignored other possible systematic differences in observing the CP asymmetries in the two modes such as the fact that the vertexing efficiencies may be different in the two cases, or that the purity required of the kaon tag may be different. We deem these to be subjects for a more detailed analysis than undertaken here.

When doing the integral in Eq. (A5) we utilize a common lower limit of 0.6 ps corresponding to a resolvable separation of 100 μ for the two B's in the BABAR environment, and optimize the upper bound to get the best CP signal. The $\Delta C = +1$ mode is particularly sensitive to the vertexing resolution since the smallness of the $D(t)$ at early times [cf Eq. (2.1)] combined with the lack of exponential suppression from the B lifetime, implies that one could significantly enhance the CP signal by giving more weight to the early time region.

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