Large CP Violation in $B \to K^{(*)}X$ Decays

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Abstract. We consider the possibility of observing CP violation in quasi-inclusive decays of the type $B^- \to K^-X$, $B^- \to K^*^-X$, $\bar{B}^0 \to K^-X$ and $\bar{B}^0 \to K^*^-X$, where $X$ does not contain strange quarks. We present estimates of rates and asymmetries for these decays in the Standard Model and comment on the experimental feasibility of observing CP violation in these decays at future $B$ factories. We find the rate asymmetries can be quite sizeable.

I INTRODUCTION

The possibility of observing large CP violating asymmetries in the decay of $B$ mesons motivates the construction of high luminosity $B$ factories at several of the world’s high energy physics laboratories. The theoretical and the experimental signatures of these asymmetries have been extensively discussed elsewhere [1], [2], [3], [4], [5]. At asymmetric $B$ factories, it is possible to measure the time dependence of $B$ decays and therefore time dependent rate asymmetries of neutral $B$ decays due to $B-\bar{B}$ mixing. The measurement of time dependent asymmetries in the exclusive modes $\bar{B}^0 \to \psi K_s$ and $\bar{B}^0 \to \pi^+\pi^-$ will allow the determination of the angles in the Cabbibo-Kobayashi-Maskawa unitarity triangle. This type of CP violation has been studied extensively in the literature.

Another type of CP violation also exists in $B$ decays, direct CP violation in the $B$ decay amplitudes. This type of CP violation in $B$ decays has also been discussed by several authors although not as extensively. For charged $B$ decays calculation of the magnitudes of the effects for some exclusive modes and inclusive modes have been carried out [6], [7], [8], [9], [10], [11], [12]. In contrast to asymmetries induced by $B-\bar{B}$ mixing, the magnitudes have large hadronic uncertainties, especially for the exclusive modes. Observation of these asymmetries can be used to rule out the superweak class of models [13].

In this paper we describe several quasi-inclusive experimental signatures which could provide useful information on direct CP violation at the high luminosity facilities of the future. One of the goals is to increase the number of events available
at experiments for observing a CP asymmetry. In particular we examine the inclusive decay of the neutral and the charged $B$ to either a charged $K$ or a charged $K^*$ meson. By applying the appropriate cut on the kaon (or $K^*$) energy one can isolate a signal with little background from $b \to c$ transitions. Furthermore, these quasi-inclusive modes are expected to have less hadronic uncertainty than the exclusive modes, would have larger branching ratios and, compared to the purely inclusive modes they may have larger CP asymmetries. In this paper we will consider modes of the type $B \to K(K^*)X$ that have the strange quark only in the $K(K^*)$-meson.

In the sections which follow, we describe the experimental signature and method. We then calculate the rates and asymmetries for inclusive $B^- \to K^-(K^{*-})$ and $\bar{B}^0 \to K^-(K^{*-})$ decays.

II EXPERIMENTAL SIGNATURES FOR QUASI-INCLUSIVE $B \to SG^*$

In the $\Upsilon(4S)$ center of mass frame, the momentum of the $K^{(*)-}$ from quasi-two body $B$ decays such as $B \to K^{(*)-}X$ may have momenta above the kinematic limit for $K^{(*)-}$ mesons from $b \to c$ transitions. This provides an experimental signature for $b \to sg^*$, $g^* \to uu$ or $g^* \to dd$ decays where $g^*$ denotes a gluon. This kinematic separation between $b \to c$ and $b \to sg^*$ transitions is illustrated by a generator level Monte Carlo simulation in Figure 1 for the case of $B \to K^{*-}$. (The $B \to K^-$ spectrum will be similar). This experimental signature can be applied to the asymmetric energy $B$ factories if one boosts backwards along the $z$ axis into the $\Upsilon(4S)$ center of mass frame.

Since there is a large background (“continuum”) from the non-resonant processes $e^+e^- \to q\bar{q}$ where $q = u,d,s,c$, experimental cuts on the event shape are also imposed. To provide additional continuum suppression, the “$B$ reconstruction” technique has been employed. The requirement that the kaon and $n$ other pions form a system consistent in beam constrained mass and energy with a $B$ meson dramatically reduces the background. After these requirements are imposed, one searches for an excess in the kaon momentum spectrum above the $b \to c$ region. Only one combination per event is chosen. No effort is made to unfold the feed-across between submodes with different values of $n$.

Methods similar to these have been successfully used by the CLEO II experiment to isolate a signal in the inclusive single photon energy spectrum and measure the branching fraction for inclusive $b \to s\gamma$ transitions and to set upper limits on $b \to s\phi$ transitions [14], [15]. It is clear from these studies that the $B$ reconstruction method provides adequate continuum background suppression.

The decay modes that will be used here are listed below:

1. $B^- \to K^{(*)-}\pi^0$
2. $\bar{B}^0 \to K^{(*)-}\pi^+$
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**FIGURE 1.** Generated Inclusive $B \to K^{*-}$ momentum spectrum. The component below 2.0 GeV/c is due to $b \to c$ decays while the component above 2.0 GeV/c arises from quasi-two body $b \to sg^*$ decay. The normalization of the $b \to c$ component is reduced by a factor of approximately 100 so that both components are visible.

3. $B^- \to K^{(*)-}\pi^-\pi^+$
4. $\bar{B}^0 \to K^{(*)-}\pi^+\pi^0$
5. $\bar{B}^0 \to K^{(*)-}\pi^+\pi^-\pi^+$
6. $B^- \to K^{(*)-}\pi^+\pi^-\pi^0$
7. $B^- \to K^{(*)-}\pi^+\pi^-\pi^+\pi^-$
8. $\bar{B}^0 \to K^{(*)-}\pi^+\pi^-\pi^+\pi^0$

In case of multiple entries for a decay mode, we choose the best entry on the basis of a $\chi^2$ formed from the beam constrained mass and energy difference (i.e. $\chi^2 = (M_B/\delta M_B)^2 + (\Delta E/\delta \Delta E)^2$). In case of multiple decay modes per event, the best decay mode candidate is picked on the basis of the same $\chi^2$.

Cross-feed between different $b \to sg$ decay modes (i.e. the misclassification of decay modes) provided the $K^{(*)-}$ is correctly identified, is not a concern as the goal is to extract an inclusive signal. The purpose of the $B$ reconstruction method is to reduce continuum background. As the multiplicity of the decay mode increases, however, the probability of misreconstruction will increase.

The signal is isolated as excess $K^{(*)-}$ production in the high momentum signal region ($2.0 < p_{K^{(*)}} < 2.7$ GeV) above continuum background. To reduce contamination from high momentum $B \to \pi^- (\rho^-)$ production and residual $b \to c$
background, we assume the presence of a high momentum particle identification system as will be employed in the BABAR, BELLE, and CLEO III experiments.

We propose to measure the asymmetry 
\[ \frac{N(K^*(+)-K^*(-))/N(K^*(+)+K^*(-))}{N(K^*(+)-n\pi^0)} \]
where \( K^*(\pm) \) originates from a partially reconstructed \( B \) decay such as \( B \to K^*(n\pi^0) \) where the additional pions have net charge 0 and \( n \leq 4 \) and one neutral pion is allowed and \( 2.7 > p(K^*(-)) > 2.0 \) GeV. We assume that the contribution from \( B \to K^-\eta'X \) decays has been removed by cutting on the \( \eta' \) region in \( X \) mass. It is possible that the anomalously large rate from this source [16,17] could dilute the asymmetry.

**FIGURE 2.** Monte Carlo simulation of inclusive \( B \to K^*-X \) signal with the B reconstruction method: (a) The beam constrained mass distribution (b) The distribution of energy difference (c) The \( K^-\pi^0 \) invariant mass after selecting on energy difference and beam constrained mass
III EFFECTIVE HAMILTONIAN

In the Standard Model (SM) the amplitudes for hadronic $B$ decays of the type $b \to qff$ are generated by the following effective Hamiltonian [18]:

$$H_{\text{eff}}^q = \frac{G_F}{\sqrt{2}} [V_{tb} V_{tq}^* (c_1 O_{1f}^q + c_2 O_{2f}^q) - \sum_{i=3}^{10} (V_{ub} V_{cq}^* e_i^u + V_{cd} V_{cq}^* e_i^c + V_{tb} V_{tq}^* e_i^t)] + \text{H.C.} ,$$

(1)

where the superscript $u$, $c$, $t$ indicates the internal quark, $f$ can be $u$ or $c$ quark. $q$ can be either a $d$ or a $s$ quark depending on whether the decay is a $\Delta S = 0$ or $\Delta S = -1$ process. The operators $O_i^q$ are defined as

$$O_{1f}^q = \bar{q}_\alpha \gamma_\mu L f_\beta \bar{f}_\gamma L b_\alpha , \quad O_{2f}^q = \bar{q}_\alpha \gamma_\mu L f_\beta \bar{f}_\gamma L b_\alpha ,$$

$$O_{3,5}^q = \bar{q}_\alpha \gamma_\mu L b_\beta \bar{q}_\gamma L (R) q'_\alpha , \quad O_{4,6}^q = \bar{q}_\alpha \gamma_\mu L b_\beta \bar{q}_\gamma L (R) q'_\alpha ,$$

$$O_{8,10}^q = \frac{3}{2} \bar{q}_\alpha \gamma_\mu L b_\beta e_\gamma q'_\alpha \gamma_\mu R (L) q'_\alpha ,$$

(2)

where $R(L) = 1 \pm \gamma_5$, and $q'$ is summed over $u$, $d$, and $s$. $O_i$ are the tree level and QCD corrected operators. $O_{3-6}$ are the strong gluon induced penguin operators, and operators $O_{7-10}$ are due to $\gamma$ and $Z$ exchange (electroweak penguins), and "box" diagrams at loop level. The Wilson coefficients $c_i^q$ are defined at the scale $\mu \approx m_b$ and have been evaluated to next-to-leading order in QCD. The $c_i^q$ are the regularization scheme independent values obtained in Ref. [9]. We give the non-zero $c_i^q$ below for $m_t = 176$ GeV, $\alpha_s (m_Z) = 0.117$, and $\mu = m_b = 5$ GeV,

$$c_1 = -0.307 , \quad c_2 = 1.147 , \quad c_3^t = 0.017 , \quad c_4^t = -0.037 , \quad c_5^t = 0.010 , \quad c_6^t = -0.045 , \quad c_7^t = -1.24 \times 10^{-5} , \quad c_8^t = 3.77 \times 10^{-4} , \quad c_9^t = -0.010 , \quad c_{10}^t = 2.06 \times 10^{-3} ,$$

$$c_{3,5}^{u,c} = -c_{4,6}^{u,c} / N_c = P_s^{u,c} / N_c , \quad c_{7,9}^{u,c} = P_e^{u,c} , \quad c_{8,10}^{u,c} = 0$$

(3)

where $N_c$ is the number of color. The leading contributions to $P_{s,e}^i$ are given by:

$$P_s^i = \left( \frac{1}{8 \pi^2} c_2 \right) \left( \frac{16}{9} + G(m_i, \mu, q^2) \right) \quad \text{and} \quad P_e^i = \left( \frac{4 \pi m_i}{9 \mu} \right) \left( N_c c_1 + c_2 \right) \left( \frac{16}{9} + G(m_i, \mu, q^2) \right).$$

(4)

The function $G(m, \mu, q^2)$ is given by

$$G(m, \mu, q^2) = 4 \int_0^1 x (1 - x) \ln \left( \frac{m^2 - x(1-x)q^2}{\mu^2} \right) dx .$$

All the above coefficients are obtained up to one loop order in electroweak interactions. The momentum $q$ is the momentum carried by the virtual gluon in the penguin diagram. When $q^2 > 4m_b^2$, $G(m, \mu, q^2)$ becomes imaginary. In our calculation, we use $m_u = 5$ MeV, $m_d = 7$ MeV, $m_s = 200$ MeV, $m_c = 1.35$ GeV [19,20].

We assume that the final state phases calculated at the quark level will be a good approximation to the sizes and the signs of the FSI phases at the hadronic level for quasi-inclusive decays when the final state particles are quite energetic as is the case for the $B$ decays in the kinematic range of experimental interest [6].
IV MATRIX ELEMENTS FOR $B^- \rightarrow K^- X$ AND $\bar{B}^0 \rightarrow K^- X$

We proceed to calculate the matrix elements of the form $<KX|H_{\text{eff}}|B>$ which represents the process $B \rightarrow KX$ and where $H_{\text{eff}}$ has been described above. The effective Hamiltonian consists of operators with a current $\times$ current structure. Pairs of such operators can be expressed in terms of color singlet and color octet structures which lead to color singlet and color octet matrix elements. In the factorization approximation, one separates out the currents in the operators by inserting the vacuum state and neglecting any QCD interactions between the two currents. The basis for this approximation is that, if the quark pair created by one of the currents carries large energy then it will not have significant QCD interactions. In this approximation the color octet matrix element does not contribute because it cannot be expressed in a factorizable color singlet form. In our case, since the energy of the quark pairs that either creates the $K$ or the $X$ state is rather large, factorization is likely to be a good first approximation. To accommodate some deviation from this approximation we treat $N_c$, the number of colors that enter in the calculation of the matrix elements, as a free parameter. In our calculation we will see how our results vary with different choices of $N_c$. The value of $N_c \sim 2$ is suggested by experimental data on low multiplicity hadronic $B$ decays [3]. The amplitude for $B \rightarrow K^{(*)}X$ can in general be split into a three body and a two body part. Detailed expressions for the matrix elements, decay distributions and asymmetries can be found in [21]

V RESULTS AND DISCUSSION

In this section we discuss the results of our calculations. We find that there can be significant asymmetries in $B \rightarrow K(K^*)X$ decays especially in the region $E_K > 2$ GeV which is also the region where an experimental signal for such decays can be isolated. The branching ratios are of order $O(10^{-4})$ which are within reach for future B factories. The contribution of the amplitude with the top quark in the loop accounts for 60-75% of the inclusive branching fraction. However, since the top quark amplitude is large and has no absorptive part in contrast to the $c$ quark amplitude, the top quark contribution reduces the net CP asymmetry from 30-50% to about 10%. This calculation includes the contribution from electroweak penguins. We find that the electroweak penguin contributions increase the decay rates by 10-20% but reduce the overall asymmetry by 20-30%. The main sources of uncertainties in our calculation are discussed extensively in [21].

The asymmetries are sensitive to the values of the Wolfenstein parameters $\rho$ and $\eta$. The existing constraints on the values of $\rho$ and $\eta$ come from measurements of $|V_{ub}|/|V_{cb}|$, $\epsilon_K$ in the K system and $\Delta M_B$. (See Ref. [22] for a recent review). In our calculation we will use $f_B = 170$ MeV and choose $(\rho = -0.15, \eta = 0.33)$. 
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FIGURE 3. Predicted Asymmetries for $B^{-} \rightarrow K^{-} X$ and $B^{-} \rightarrow K^{*-} X$ as a function of the kaon energy. The three sets of curves indicate the sensitivity of the asymmetry to the value of $N_c$. The values $N_c = 2, 3, \infty$ are considered.

TABLE 1. Integrated decay rates and asymmetries for $B \rightarrow K^{(*)} X$ Decay

| Process                  | Branching Ratio $(1.65 \times 10^{-4})$ | Integrated Asymmetry |
|--------------------------|----------------------------------------|----------------------|
| $B^{-} \rightarrow K^{-} X$ | 1.02, 0.79, 1.20                       | $-0.10, -0.11, -0.050$ |
| $B^{-} \rightarrow K^{-} X (E_{K} \geq 2.1 \text{GeV})$ | 0.81, 0.74, 0.77                       | $-0.12, -0.12, -0.07$ |
| $B^{0} \rightarrow K^{-} X$ | 0.6, 0.7, 0.8                           | $-0.12, -0.12, -0.13$ |
| $B^{-} \rightarrow K^{*-} X$ | 1.37, 1.24, 2.30                       | $-0.11, -0.14, -0.11$ |
| $B^{-} \rightarrow K^{*} X (E_{K^{*}} \geq 2.1 \text{GeV})$ | 1.05, 1.16, 1.67                       | $-0.14, -0.15, -0.14$ |
| $B^{0} \rightarrow K^{*} X$ | 1.05, 1.16, 1.39                       | $-0.15, -0.15, -0.16$ |

In Fig. 3 we show the asymmetries for $K$ and $K^{*}$ in the final state in charged $B$ decays for different values of $N_c$. Variation of the asymmetries with the different inputs in our calculation are presented in detail in [21].

In Table. 1 we give the branching fractions and the integrated asymmetries for the inclusive decays for different $N_c$, $q^2 = m_b^2/2$ ( $q$ is the gluon momentum in the two body part of the amplitude ), $f_B = 170$ MeV, $\rho = -0.15, \eta = 0.33$. For the charged $B$ decays we also show the decay rates and asymmetries for $E_{K} > 2$ (2.1) GeV as that is the region of the signal.

The above figures show that there can be significant asymmetries in $B \rightarrow K^{(*)} X$ decays, especially in the region $E_{K} > 2$ GeV which is the region of experimental sensitivity for such decays. As already mentioned, our calculation is not free of theoretical uncertainties. Two strong assumptions used in our calculation are the use
of quark level strong phases for the FSI phases at the hadronic level and the choice of the value of the gluon momentum $q^2$ in the two body decays. Other uncertainties from the use of different heavy to light form factors, the use of factorization, the model of the B meson wavefunction, the value of the charm quark mass and the choice of the renormalization scale $\mu$ have smaller effects on the asymmetries [21].

VI CONCLUSION

We find significant direct CP violation in the inclusive decay $B \rightarrow K^- X$ and $B \rightarrow K^{*-} X$ for $2.7 > E_{K^{(*)}} > 2.0$ GeV. The branching fractions are in the $10^{-4}$ range and the CP asymmetries may be sizeable. These asymmetries should be observable at future B factories and could be used to rule out the superweak class of models.

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