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# Direct CP violation in $b \to dJ/\psi$ decays

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## Abstract

We investigate the possibility of observing direct CP violation in self-tagging B-meson decays of the type $b \to dJ/\psi$. The CP asymmetry can be generated due to strong or electromagnetic scattering in the final state, or due to long distance effects. The first two contributions give asymmetries of *a few* $\times 10^{-3}$, in the standard model. The long distance effects are hard to estimate, but it cannot be excluded that they yield asymmetries of about 1%.
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The standard model (SM) predicts the existence of relative CP-odd phases between different B-meson decay amplitudes (direct CP violation). If two such amplitudes contribute coherently to a decay $B \to f$, they may generate a CP asymmetry

$$a_{CP} = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})}. \quad (1)$$

This type of asymmetry does not require mixing, and it can occur in self-tagging decay modes. These are decays such that $B \not\to \bar{f}$ and $\bar{B} \not\to f$ (e.g. decays of charged B-mesons), and so the distinction between $B$ and $\bar{B}$ is immediate, given the final state. As a result, the experimental sensitivity is improved by one order of magnitude with respect to the case of the neutral B-meson decays into CP eigenstates, where the tagging is more involved [1].

In the SM, the numerator of eq. 1 is proportional to $\sin^6 \theta_C$, and so the asymmetry can be significant only for decays that are strongly Cabibbo suppressed. The asymmetries in rare decays to charmless states (with neither bare nor hidden charm) have been calculated in earlier works [2, 3, 4]: for typical values of the parameters in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, the 1-loop level decays such as $b \to ds\bar{s}$ and $b \to d\gamma$ have asymmetries of about 5%. The tree level decays, such as $b \to du\bar{u}$, and the Cabibbo favored $b \to s$ transitions have asymmetries that are one order of magnitude lower. Exclusive decays have also been discussed: their asymmetries should be of the same order as those in the corresponding semi-inclusive processes, but (except for the case of the radiative decays) there are uncertainties from the hadronic form factors, as well as non-perturbative contributions that are difficult to estimate and could be large. The branching ratios are of the order of $10^{-6}$ for decays such as $B^- \to K_S K^-$ and $B_s^0 \to \bar{K}^{*0}\gamma$. Only future experiments, with appropriate triggering and good $K/\pi$ separation, will be able to probe the asymmetries in these modes, at a level anywhere near the SM predictions [5].

The self-tagging decays of the type $b \to dc\bar{c}$, where the charm-anticharm pair forms a $J/\psi$, may show CP violating effects [6]. The size of those effects is investigated in this paper. The modes with a $J/\psi$ are particularly attractive from the experimental point of view, as one can trigger on the $J/\psi$ *via* its dilepton decay mode. Moreover, this is feasible at hadronic accelerators (as demonstrated by the current results from CDF [7]), where large numbers of B-mesons can be produced. The branching ratio for the $b \to dJ/\psi$ transition is approximately $\sin^2\theta_C \times BR(B \to J/\psi\ anything) \simeq 5 \times 10^{-4}$, and the branching ratios for the exclusive decays, such as $B^- \to J/\psi\pi^-$ or $B_s^0 \to J/\psi\bar{K}^{*0}$, are one order of magnitude lower. With an expected sample of $10^{10}$ B-mesons, and provided a detection efficiency (including $K/\pi$ separation) no lower than 10%, the asymmetries in the exclusive modes can be probed down to around 1% (at the $3\sigma$ level).

Here, we estimate the value of the CP asymmetry that is predicted by the SM for these modes. As is always the case for the asymmetries that are due to direct CP violation, the difficulty lies in estimating the strength of the final state interactions. We will point out that the 1-gluon mediated scattering [2], that is expected to dominate in the case of the charmless decays that were mentioned above, does not contribute to the asymmetry in $b \to dJ/\psi$. We then proceed to discuss the main contributions to the final state scattering in this case. For each one of them, the resulting asymmetry is either calculated, or an attempt is made to give a reasonable estimate. We will find that the asymmetry that is predicted in the SM lies at the level, or slightly below, the experimental sensitivity that is expected in the near future.

The tree contribution to the $b \to dJ/\psi$ decay amplitude is $V_{cb}V_{cd}^*T_{d\psi}$. With

$$< 0|\bar{c}\gamma_\mu c|J/\psi >= m_{J/\psi}f_{J/\psi}\epsilon_\mu, \tag{2}$$

factorization gives

$$T_{d\psi} = G_F\frac{1}{\sqrt{2}}a_1 m_{J/\psi}f_{J/\psi}\epsilon_\mu^*\bar{u}_d\gamma^\mu(1-\gamma_5)u_b. \tag{3}$$

Because the $c\bar{c}$ pair must be in a color singlet, there is a color suppression factor $a_1$. Including the leading-logarithm QCD corrections, $a_1 = C_1(m_b) + C_2(m_b)/N_c$ [8] and the Wilson coefficients are [9]

$$\begin{aligned} C_1(m_b) &= 0.25 \\ C_2(m_b) &= -1.11, \end{aligned} \tag{4}$$

for $\Lambda_{\overline{MS}}^{(4)} = 200MeV$ [10] and $m_b = 4.8GeV$. The CP asymmetry arises from the interference between the tree decay amplitude, and any additional term that has a different CP-odd phase and a different CP-even phase. The latter phase appears when the additional contribution is due to the decay into an on-mass-shell intermediate state that then scatters into $dJ/\psi$, through final state interactions. The intermediate state that is favored is $du\bar{u}$, since it is fed by a tree level decay amplitude $V_{ub}V_{ud}^*T_{du\bar{u}}$. When the scattering $u\bar{u} \to J/\psi$ can be treated perturbatively, we have

$$\bar{A} \equiv A(b \to dJ/\psi) = V_{cb}V_{cd}^*T_{d\psi} + i\frac{1}{2}V_{ub}V_{ud}^*T_{du\bar{u}}A(u\bar{u} \to J/\psi). \qquad (5)$$

The interference between the two terms on the RHS gives the difference

$$|A|^2 - |\bar{A}|^2 = 2Im\{V_{cb}^*V_{cd}V_{ub}V_{ud}^*\}T_{d\psi}^*T_{du\bar{u}}A(u\bar{u} \to J/\psi), \qquad (6)$$

(the sum over the spin, color and phase space of the intermediate state is implied), and hence the CP asymmetry of eq. 1.

In the rare decays into charmless final states that have been studied in the literature, the final state scattering occurs through order $\alpha_s$ diagrams [2]. For example, for the asymmetry in $b \to ds\bar{s}$, the additional term in the amplitude is mostly due to $b \to du\bar{u} \xrightarrow{g} ds\bar{s}$. In the case of $b \to du\bar{u} \to dJ/\psi$ (and within the factorization approximation), the 1-gluon scattering cannot contribute as the $J/\psi$ is a color singlet. Because the strong interaction is invariant under charge conjugation, the 2-gluon amplitude also vanishes. The QCD scattering can then occur only at the order $\alpha_s^3$, and it is comparable to the electromagnetic scattering [11].

A rough estimate shows that the QCD and QED scatterings from the $du\bar{u}$ intermediate state are indeed of similar strength. The ratio of these two contributions,

$$A(u\bar{u} \xrightarrow{QCD} J/\psi)/A(u\bar{u} \xrightarrow{QED} J/\psi), \qquad (7)$$

is of the same order as $|\Gamma(J/\psi \xrightarrow{QCD} u\bar{u})/\Gamma(J/\psi \xrightarrow{QED} u\bar{u})|^{1/2}$. The QED width is equal to 2/3 of $\Gamma(J/\psi \xrightarrow{QED} hadrons) = (17.0 \pm 2.0)\% \times \Gamma_{J/\psi}$. The QCD width is some fraction (not too different from the 1/3 of a naive constituent picture) of $\Gamma(J/\psi \xrightarrow{QCD} hadrons) = \Gamma(J/\psi \to hadrons) - \Gamma(J/\psi \xrightarrow{QED} hadrons) = (69.0 \pm 2.8)\% \times \Gamma_{J/\psi}$. It follows that the ratio in eq. 7 is $\sim 1.5$.

Of the two similar contributions, the electromagnetic one is simpler to calculate. The convolution of the amplitude for the decay $b \to du\bar{u}$ and that for the 1-photon scattering $u\bar{u} \to J/\psi$ gives

$$\begin{aligned} T_{du\bar{u}} A(u\bar{u} \to J/\psi) &= -G_F \sqrt{2} \alpha Q_u Q_c a_1 \\ & \quad m_{J/\psi} f_{J/\psi} \epsilon^*_\mu \bar{u}_d \gamma^\mu (1-\gamma_5) u_b \\ &= -T_{d\psi} 2\alpha Q_u Q_c \end{aligned} \tag{8}$$

The contribution to the asymmetry in the semi-inclusive decay $b \to dJ/\psi$ is then

$$a_{CP} \simeq -\eta \alpha 8/9 = -0.3\%, \tag{9}$$

where $\alpha(m_{J/\psi}) = 1/133$, and $\eta = 0.4$ has been chosen as a typical value for the CKM parameter, within the present bounds [12]. This result should also hold for the exclusive decays. The reason is that the two terms in the decay amplitude (analogous to those in eqs. 3 and 8) have the same operator structure. Then the hadronic matrix element can be factored out, and the expression for the asymmetry is that given in eq. 9.

So far we have ignored the effect of the intermediate state $dc\bar{c}$. For the case of the inclusive decay, $b \to dc\bar{c}$, that effect is just a re-scattering of the final state. It does not generate two amplitudes (with different CKM phases) that can interfere, and so there is no contribution to the asymmetry [4]. But for the exclusive or semi-inclusive cases that we are discussing, the situation is different. It has been pointed out by Wolfenstein [4] that contributions to the asymmetry, from intermediate states with the same quark content as the final state, will arise, once the small penguin amplitudes are added to the tree amplitudes considered so far. For example, the amplitude for a decay such as $B^- \to J/\psi\pi^-$ becomes

$$\begin{aligned} A(B^- \to J/\psi\pi^-) &= V_{cb} V^*_{cd} T_{\psi\pi^-} + V_{tb} V^*_{td} P_{\psi\pi^-} \\ &+ i\frac{1}{2} \sum_X \left( V_{cb} V^*_{cd} T_X + V_{tb} V^*_{td} P_X \right) A(X \to J/\psi\pi^-). \end{aligned} \tag{10}$$

The penguin amplitudes are the terms proportional to $V_{tb}V^*_{td}$, and we have included the absorptive part due to the intermediate states $X$. These are the states $D^0 D^-$, $D^{*-} D^0$, $J/\psi\rho^-$, etc., that have the same quark content as the final state $J/\psi\pi^-$ (for clarity, we now omit the absorptive part due to $b \to du\bar{u} \to dc\bar{c}$ that was discussed before). Because the matrix elements of the tree and penguin operators depend on the hadronic states, the penguin/tree ratios $P_{\psi\pi^-}/T_{\psi\pi^-}$ and $P_X/T_X$ will in general be different. Then, the dispersive and absorptive parts of the amplitude in eq. 10 will have different CKM phases, and so the states $X$ will contribute to the CP asymmetry with

$$a_{CP} \simeq Im\{\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*}\}\sum_X \frac{T_{\psi\pi^-}^* T_X A(X \to J/\psi\pi^-)}{|T_{\psi\pi^-}|^2}(\frac{P_X}{T_X} - \frac{P_{\psi\pi^-}}{T_{\psi\pi^-}}). \qquad (11)$$

The final state scatterings $A(X \to J/\psi\pi^-)$ are long distance effects that are hard to estimate. We will compute the asymmetry due to some of the intermediate states $X$, leaving the ratio

$$\xi_X \equiv \frac{T_{\psi\pi^-}^* T_X A(X \to J/\psi\pi^-)}{|T_{\psi\pi^-}|^2} \qquad (12)$$

as an undetermined parameter. In particular, we will look at intermediate states such as $D^0D^-$, where $c\bar{c}$ is not required to form a color singlet. There, the amplitude for the decay $B \to X$ is not color suppressed, and the parameter $\xi_X$ may be larger. Notice that, if the branching ratio for $B^- \to J/\psi\pi^-$ can be measured with sufficient precision (and if the short distance contribution is well understood), then some information can be obtained on the strength of the final state scatterings (barring possible cancellations between the different intermediate states $X$). For the moment, let us just assume that $A(X \to J/\psi\pi^-)$ can be treated perturbatively (so that eqs. 10 and 11 remain valid).

The tree and penguin decay amplitudes are calculated from the effective Hamiltonian

$$\begin{aligned} H_{eff} &= -\frac{G_F}{\sqrt{2}}[V_{ub}V_{ud}^*(C_1Q_1^u + C_2Q_2^u) + V_{cb}V_{cd}^*(C_1Q_1^c + C_2Q_2^c) \\ &\quad + V_{tb}V_{td}^*\sum_{k=3}^{6} C_kQ_k + h.c.], \end{aligned} \qquad (13)$$

where

$$\begin{aligned} Q_1^l &= \bar{d}\gamma^\mu(1-\gamma_5)b\ \bar{l}\gamma_\mu(1-\gamma_5)l \\ Q_2^l &= \bar{l}\gamma^\mu(1-\gamma_5)b\ \bar{d}\gamma_\mu(1-\gamma_5)l \\ Q_3 &= \sum_{l=u,d,s,c,b} \bar{d}\gamma^\mu(1-\gamma_5)b\ \bar{l}\gamma_\mu(1-\gamma_5)l \end{aligned}$$

$$
\begin{aligned}
Q_4 &= \sum_{l=u,d,s,c,b} \bar{l}\gamma^\mu(1-\gamma_5)b\ \bar{d}\gamma_\mu(1-\gamma_5)l \\
Q_5 &= \sum_{l=u,d,s,c,b} \bar{d}\gamma^\mu(1-\gamma_5)b\ \bar{l}\gamma_\mu(1+\gamma_5)l \\
Q_6 &= -2\sum_{l=u,d,s,c,b} \bar{l}(1-\gamma_5)b\ \bar{d}(1+\gamma_5)l,
\end{aligned} \tag{14}
$$

and, for $\Lambda^{(4)}_{\overline{MS}} \simeq 200MeV$, the Wilson coefficients are [9]

$$
\begin{aligned}
C_3(m_b) &= 0.011 \\
C_4(m_b) &= -0.026 \\
C_5(m_b) &= 0.008 \\
C_6(m_b) &= -0.032
\end{aligned} \tag{15}
$$

($C_1$ and $C_2$ were given in eq. 4). We use factorization and neglect the terms of order $1/N_c$ [8]. For the decays of the type $b \to dJ/\psi$, the penguin to tree ratio is

$$\frac{P_{d\psi}}{T_{d\psi}} = \frac{C_3 + C_5}{C_1} = 0.076. \tag{16}$$

Whereas for $B^- \to D^0 D^-$, and for some other color favored decays, we find

$$
\begin{aligned}
\frac{P_{D^-D^0}}{T_{D^-D^0}} &= \frac{1}{C_2}(C_4 + 2C_6 \frac{1}{m_b - m_c}\frac{m_D^2}{m_c + m_d}) = 0.064 \\
\frac{P_{D^-D^{*0}}}{T_{D^-D^{*0}}} &= \frac{1}{C_2}(C_4 - 2C_6 \frac{1}{m_b + m_c}\frac{m_D^2}{m_c + m_d}) = 0.0021 \\
\frac{P_{D^{*-}D^0}}{T_{D^{*-}D^0}} &= \frac{P_{D^{*-}D^{*0}}}{T_{D^{*-}D^{*0}}} = \frac{C_4}{C_2} = 0.023
\end{aligned} \tag{17}
$$

(with $m_c = 1.5GeV$ and $m_d \ll m_c$). The equations of motion have been used to relate the different matrix elements, so that the hadronic uncertainties always cancel in the penguin/tree ratios. For some of these ratios, the effect of 1-loop electroweak corrections [6] can be significant. A thorough analysis of such contributions, including QCD corrections, can be found in ref. [13]. Using the results in there, we derive the corrected values for the penguin/tree ratios: $P_{d\psi}/T_{d\psi} = 0.042$ and $P_{D-D^{*0}}/T_{D-D^{*0}} = 0.0012$; whereas for the other decays, the electroweak effects are not larger than 10%. Replacing these values in eq. 11, one finds contributions to the asymmetry of about

$$a_{CP} = \xi_X \times 1\% \tag{18}$$

(for $\eta = 0.4$). This number should give us a rough idea of the size of the asymmetries (for either the semi-inclusive or the exclusive cases), that are expected from the long distance effects. Although, there are contributions from many channels that add with different signs, it is unlikely that large cancellations or enhancements will occur. Therefore, according to the size of $\xi_X$, the contribution in eq. 18 could be comparable to the short distance effects described before, and give an asymmetry slightly below the expected experimental sensitivity. But it could also be the dominant effect, and then the asymmetry will be within reach of the ongoing experiments at the Tevatron.

We should stress that our results were derived using factorization, together with the prescription of dropping $1/N_c$ contributions to the hadronic matrix elements in the decay amplitudes [8]. This is the same prescription that is successful in predicting the branching ratios for the decays of the type $b \to sJ/\psi$. Different results would follow, for example, by taking $N_c = 3$. In that case, some new mechanism must contribute to the color suppressed decays, that would affect the branching ratio, and most certainly, also the asymmetry.

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better model. It should be pointed out that this is only relevant in the last part of this work, when estimating the penguin contributions for which there is no experimental guidance so far.

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