Charming penguin and direct CP-violation in charmless $B$ decays

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ABSTRACT

In the study of two-body charmless $B$ decays as a mean of looking for direct CP-violation and measuring the CKM mixing parameters in the Standard Model, the short-distance penguin contribution with its absorptive part generated by charm quark loop seems capable of producing sufficient $B \to K\pi$ decays rates, as obtained in factorization and QCD-improved factorization models. However there are also long-distance charming penguin contributions which could give rise to a strong phase due to the rescattering $D^*D_s^* \to K\pi$ etc. In this talk, I would like to discuss recent works on the charming penguin contribution as a different approach to the calculation of these contributions in two-body charmless $B$ decays. We find that the charming penguin contribution is significant for $B \to K\pi$ decays and, together with the tree and penguin terms, produces large branching ratios in agreement with data, though the analysis is affected by large theoretical uncertainties. The absorptive part due to the charmed meson intermediate states is found to produce large CP asymmetries for $B \to K\pi, \pi\pi$ decays.
In nonleptonic charmless two-body $B$ decays, the interference between the tree-level and penguin terms make it possible to look for direct CP-violation and to determine the CP-violating weak CKM phase angle $\gamma$ from these decays [1, 2, 3]. It is known that the top quark penguin amplitude is insufficient to produce a large $B \rightarrow K\pi$ decay rates. When the effects of charm quark loop are included, the decay rate is enhanced [4, 5, 6, 7, 8] and are in qualitative agreement with data [8, 9, 10, 11]. The effects of charm quark loop is contained in QCD-improved factorization as shown recently [12, 13, 14].

One can also take the view that these charm quark loop contributions are basically long-distance effects, essentially due to charmed meson rescattering processes, such as, e.g. $B \rightarrow D_s D \rightarrow K\pi$. These contributions, first discussed in [15], have been more recently stressed by [16, 17] where they are called the charming penguin contributions. In [18, 19], we have evaluated these contributions and found that both the absorptive and the real part of the charming penguin are large, comparable to the short-distance part and is capable of generating large CP asymmetries in charmless $B$ decays. In this talk I would like to discuss these calculations and stress the importance of the charming penguin in charmless $B$ decays, especially the large absorptive part generated by the charmed meson rescattering effects and the CP asymmetries obtained. That the charmed meson rescatterings could generate a large charming penguin is easily seen from the unitarity of the $S$–matrix. For example, the absorptive part of the $B \rightarrow K\pi$ decays amplitude would get the main contribution from the $D_s D$ and $D_s^* D^*$ intermediate states since the color-favored, Cabibbo-allowed $B \rightarrow D_s D$ and $B \rightarrow D_s^* D^*$ decays which are governed by the large coefficient $a_2 = 1.03$ have branching ratios of the order $10^{-2}$ compared with the penguin-dominated $B \rightarrow K\pi$ decays with branching ratios a few $10^{-5}$. Without the suppression of the process $D_s D \rightarrow K\pi$ and $D_s^* D^* \rightarrow K\pi$, we would have a very large $B \rightarrow K\pi$ decay rates.

In the standard model, the effective Hamiltonian for $B \rightarrow K\pi$ decays are given by

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ub} V_{us}^* (c_1 O_{1u}^1 + c_2 O_{2u}^1) + V_{cb} V_{cs}^* (c_1 O_{1c}^c + c_2 O_{2c}^c) + c_2 O_{2c}^c - V_{tb}^* V_{ts} \sum_{i=3}^{10} c_i O_i + c_g O_g + \text{h.c.},$$

where $c_i$ are next-to-leading Wilson coefficients at the normalization scale $\mu = m_b$ [5, 7, 20, 21, 22]. $V_{ab}$ etc. are elements of the unitary Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix relating the weak interaction eigenstate of $d, s, b$ quark to their mass eigenstate [23]. The CP-violating weak phase $\gamma = \arg(-V_{ud} V_{ub}^* / V_{cd} V_{cb}^*)$ produces CP asymmetries in charmless $B$ decays. The tree-level operators $O_{1i}^c, O_{2i}^c$, the penguin operators $O_i$ ($i = 3, ..., 10$) and the chromomagnetic gluon operator $O_g$ give the short-distance amplitude. The operators $O_{1i}^c, O_{2i}^c$ contribute to the $B \rightarrow K\pi$ decay amplitudes only through loop generated by the charmed meson intermediate states with the absorptive part given by the process $B \rightarrow D_s D \rightarrow K\pi$ and $B \rightarrow D_s^* D^* \rightarrow K\pi$ and the real part by the following expression based on the light-cone expansion [24, 25]

$$A_{LD} = K \langle K^0 \pi^+ | : J_\mu(0) \hat{J}^\mu(0) : | B^+ \rangle$$
\[ \approx K \int \frac{d^4 \vec{n}}{4\pi} \langle K^0 \pi^+ | T(J_\mu(x_0) \hat{J}_\mu(0)) | B^+ \rangle \]

with \( J_\mu = \bar{b} \gamma_\mu (1 - \gamma_5) c \) and \( \hat{J}_\mu = \bar{c} \gamma_\mu (1 - \gamma_5) s \). \( a_2 = (c_2 + c_1/3) (= 1.03) \) \( c_1 \) and \( c_2 \) are Wilson coefficients, and \( K = \frac{G_F}{\sqrt{2}} a_2 V_{cb}^* V_{cs} \), \( x_0 = (0, \vec{n}/\mu) \) with \( |\vec{n}| = 1 \) and \( \mu \) sufficiently large (\( \mu \approx m_b \)) so that \( O(x_0^2) \) terms become negligible. \( \mu \) acts as a separation between short-distance physics (in the Wilson coefficients) and the long-distance physics which is dominated by the hadronic states and resonances. We have,

\[ A_{LD} = K \int \frac{d^4 q}{(2\pi)^4} \theta(q^2 + \mu^2) T(q) \]

\[ T(q) = \int d^4 x e^{+iq_x} \langle K^0 \pi^+ | T(J_\mu(x) \hat{J}_\mu(0)) | B^+ \rangle \]

and the high frequency part has been cut-off from the \( q \) integral by \( \theta(q^2 + \mu^2) \) to simplify computations. To compute \( A_{LD} \), we saturate \( T(q) \) with the \( D, D^* \) intermediate states. These pole terms are then obtained in terms of the \( B \rightarrow D, D^* \) and \( D \rightarrow K\pi \) and \( D^* \rightarrow K\pi \) semi-leptonic decay form factors at each vertex of the pole diagrams and are given by heavy quark effective theory and chiral effective lagrangian with the form factors extrapolated to hard meson momenta. The strong \( DD^*\pi \) coupling constants with hard pion as in \( B \rightarrow K\pi \) decay can be obtained by a suppression factor relative to the soft pion limit by \( G_{D^*D\pi} = \frac{2m_D}{\sqrt{2}} F(|\vec{p}_\pi|) \), \( F(|\vec{p}_\pi|) \) is normalized by \( F(0) = 1 \) and \( g \approx 0.4 \) in the soft pion limit. For \( |\vec{p}_\pi| \approx m_B/2 \), \( F(|\vec{p}_\pi|) = 0.065 \pm 0.035 \) in the constituent quark model.

Since the threshold for the \( D_s, D \) and \( D_s^*, D^* \) production is below the \( B \) meson mass, the \( D_s \) and \( D_s^* \) pole term for the \( D, D^* \rightarrow K\pi \) form factors have an absorptive part. This pole term is in fact a rescattering term via the Cabibbo-allowed \( B \rightarrow D_s D \) decays followed by the strong annihilation process \( D_s D \rightarrow K\pi \) and can be obtained from the unitarity of the \( B \rightarrow K\pi \) decay amplitude. We have, for the \( D_s D \) channel,

\[ \text{Disc} A_{LD} = -\frac{m_D}{16\pi^2 m_B^2} \sqrt{\omega^2 - 1} \times \int d\vec{n} A(B-D_s D) A(D_s D \rightarrow K\pi) \],

and similar expressions for the \( D_s^* D^* \) contribution. To compute the absorptive part, we use factorization model which reproduces well the \( B \rightarrow D_s D, B \rightarrow D_s^* D^* \) decay rates. \( A(D_s D \rightarrow K\pi) \), \( A(D_s^* D^* \rightarrow K\pi) \) are given by the \( t \)-channel \( D, D^* \) exchange Born terms which are \( O(G_{D^*D}\pi)^2 \). However the rescattering amplitudes \( A(D_s D \rightarrow K\pi) \) and \( A(D_s^* D^* \rightarrow K\pi) \) in the \( B \) mass region, being exclusive processes at high energy, should be suppressed. This is taken into account by the suppression factor \( F(|\vec{p}_\pi|) \). As said earlier, the \( A(B \rightarrow D_s D) \) and \( A(B \rightarrow D_s^* D^*) \) amplitudes are bigger than \( A(B \rightarrow K\pi) \) by a factor \( a_2/a_0 \approx 20 \) in factorization model. Hence the absorptive part due to charmed meson rescattering effects could be large. To find the real part, we compute all Feynman diagrams for \( T(q) \) and integrate over the virtual current momentum \( q \) up to a cut-off \( \mu = m_b \). It is possible to choose a cut-off momentum by a change of variable of variable \( q = p_B - p_{D_s^*} \) to the momentum \( \ell \) defined by the formula

\[ q = p_B - p_{D_s^*} \equiv (m_B - m_{D_s^*}) v - \ell \].

(5)
Table 1: Theoretical values for \( A_{T+P} \) (Tree+Penguin amplitude) and \( A_{ChP} \) (Charming Penguin amplitude).

| Process          | \( A_{T+P} \times 10^8 \) GeV | \( A_{ChP} \times 10^8 \) GeV |
|------------------|-------------------------------|-------------------------------|
| \( B^+ \to K^0 \pi^+ \) | +1.60                        | +2.06 + 2.36i                |
| \( B^+ \to K^+ \pi^0 \) | +1.21 − 0.498i               | +1.45 + 1.67i                |
| \( B^0 \to K^+ \pi^- \) | +1.32 − 0.634i               | +2.06 + 2.36i                |
| \( B^0 \to K^0 \pi^0 \) | −0.921 − 0.0497i             | −1.45 − 1.67i                |
| \( B^+ \to \pi^+ \pi^- \) | −1.35 − 1.79i                | 0                            |
| \( B^0 \to \pi^+ \pi^- \) | −1.85 − 2.16i                | −0.576 − 0.648i              |
| \( B^0 \to \pi^0 \pi^0 \) | +0.0516 + 0.379i             | −0.576 − 0.648i              |
| \( B^+ \to K^+ \eta \) | −0.0491 − 0.415i             | +0.0830 + 0.0896i            |
| \( B^+ \to K^+ \eta' \) | +1.40 − 0.261i               | +2.53 + 2.83i                |
| \( B^0 \to K^0 \eta \) | +0.172 − 0.0418i             | +0.0830 + 0.0896i            |
| \( B^0 \to K^0 \eta' \) | +1.54 − 0.0269i              | +2.53 + 2.83i                |

As discussed in [18], the chiral symmetry breaking scale is about 1 GeV and the mean charm quark momentum \( k \) for the on-shell \( D \) meson is about 300 MeV, the virtual momentum \( \ell \) should be below 0.6 GeV, hence a cut-off \( \mu_\ell \approx 0.6 \) GeV. The real part is then given by a Cottingham formula as follows (the notations are those of [18]).

\[
\text{Re} A_{LD} = \frac{i K}{2 (2\pi)^3} \int_0^{\mu_l^2} dL^{2} \int_{\sqrt{L^2}}^{\sqrt{L^2}} \frac{d\theta}{\sqrt{L^2}} \left\{ \sum_{j=0}^\infty \frac{\bar{f}_{D}^j h_D^j}{p_D^2 - m_D^2} \left( \frac{p_D^+}{p_D^+ - m_D^+} \right) \right\}.
\]

The results of the calculations are shown in Table 1 taken from [19]. The short-distance part \( A_{T+P} \) is obtained with \( c_2 = 1.105 \), \( c_1 = -0.228 \), \( c_3 = 0.013 \), \( c_4 = -0.029 \), \( c_5 = 0.009 \), \( c_6 = -0.033 \) [26], \( \gamma = 54.8^\circ \). \( F_0^B M'(m_\pi^2) \approx F_0^B M'(0) = 0.25 \) (\( M, M' = K, \pi^\pm \)) given by QCD sum rules [27], and is smaller by 20–30% than the lattice and BWS values [8]. As seen from Table 1, the charming penguin term \( A_{ChP} \) and its absorptive part are comparable to the short-distance part. The predicted branching ratios for \( B \to K\pi \) and \( B \to \pi\pi \) decays are shown in Table 2 with results from Babar[2] and Belle[3]. We note general agreement with data considering various uncertainties on the value for the cut-off \( \mu_\ell \) and the suppression factor \( F(|\vec{p}_\ell|) \) as discussed in [18, 19]. The \( K\eta' \) modes are also enhanced by the charming penguin contribution as shown in Table 1 [19].

The CP asymmetry is \( A_{CP} = (\tilde{\Gamma} - \Gamma)/(\tilde{\Gamma} + \Gamma) \). Since \( \tilde{\Gamma} - \Gamma \) is given by 4 \( \text{Im} A_{T+P} \text{Im} A_{ChP} \) which depends only on \( \text{Im} A_{T+P} \) and the absorptive part of the charming penguin, the absolute asymmetry \( |A_{CP}| \) suffers from less uncertainties than the real part in our calculations. From the Table 1, we obtain for \( |A_{CP}| \), the value 0.16, 0.17 and 0.25 for the mode \( K^+\pi^0 \), \( K^+\pi^- \) and \( \pi^+\pi^- \), respectively. This is in contrast with small CP asymmetries predicted by
Table 2: Theoretical values for the CP averaged Branching Ratios (BR). The last two columns are the more recent BR from Babar [2] and Belle Collaboration [3].

| Process        | BR×10^6 (T+P) | BR×10^6 (T+P+ChP) | BR×10^6 (Babar) | BR×10^6 (Belle) |
|----------------|---------------|--------------------|-----------------|-----------------|
| B^± → K^0 π^±  | ~ 2.7         | 18.4 ± 10.8        | 17.5^{+1.8}_{-1.7} ± 1.3 | 19.4^{+3.1}_{-3.0} ± 1.6 |
| B^± → K^± π^0  | ~ 1.6         | 9.5 ± 5.5          | 12.8^{+1.2}_{-1.1} ± 1.0 | 13.0^{+2.5}_{-2.4} ± 1.3 |
| B^0 → K^± π^±  | ~ 1.9         | 15.3 ± 9.9         | 17.9 ± 0.9 ± 0.7 | 22.5^{+1.9}_{-1.8} ± 1.6 |
| B^0 → K^0 π^0  | ~ 0.75        | 7.4 ± 4.8          | 10.4 ± 1.5 ± 0.8 | 8.0^{+3.3}_{-3.1} ± 1.6 |
| B^± → π^± π^0  | ~ 4.8         | ~ 4.8              | 5.5^{+1.0}_{-0.9} ± 1.3 | 7.4^{+2.3}_{-2.2} ± 0.9 |
| B^0 → π^+ π^-  | ~ 7.2         | 9.7 ± 2.3          | 4.6 ± 0.6 ± 0.2 | 5.4 ± 0.12 ± 0.5 |
| B^0 → π^0 π^0  | ~ 0.06        | 0.37 ± 0.35        | < 3.6            | < 6.4           |

QCD-improved factorization [12, 13, 14] for these decays. Our values are similar to those given in [17, 28] and compatible with the measured asymmetries by Babar [2] and Belle [3] Collaborations who found smaller asymmetries but with large error. One exception is the Babar value A_{CP} = −0.102 ± 0.05 ± 0.016 for the mode K^+ π^- which is consistent with the absolute value |A_{CP}| = 0.17 we found.

In conclusion, long-distance and charmed meson rescatterings effects are capable of producing large B → Kπ decay rates and CP asymmetries. More data from Babar and Belle will tell us if these inelastic FSI rescattering effects are indeed present in charmless B decays, a rare situation in nonleptonic decays.

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