Exploring *CP* violation with B_c decays

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We point out that the pure ''tree'' decays $B_c^{\pm}\to D_s^{\pm}D$ are particularly well suited to extract the Cabibbo-Kobayashi-Maskawa angle γ through amplitude relations. In contrast with conceptually similar strategies using $B^{\pm}\to K^{\pm}D$ or $B_d\to K^{*0}D$ decays, the advantage of the B_c approach is that the corresponding triangles have three sides of comparable length and do not involve small amplitudes. Decays of the type $B_c^{\pm}\to D^{\pm}D$, the U-spin counterparts of $B_c^{\pm}\to D_s^{\pm}D$, can be added to the analysis, as well as channels, where the $D_s^{\pm}$ and $D^{\pm}$ mesons are replaced by higher resonances.

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CP violation is one of the least understood aspects of particle physics [1,2]. The standard model provides a simple description of this phenomenon through the complex Cabibbo-Kobayashi-Maskawa (CKM) matrix [3], which is consistent with present particle physics experiments. However, the baryon asymmetry of the Universe clearly requires additional sources for *CP* violation [4]; therefore *CP* violation might be the road to new physics.

Decays of B mesons provide a rich ground for investigating *CP* violation [5,6]. They allow both for stringent tests of the standard model, and for studies of new sources for this effect. Consequently, the literature in this field grows daily. Within the standard model, *CP* violation is often characterized by the so-called unitarity triangle [7] and the measurements of its three angles α, β, and γ. Many years ago, Bigi, Carter, and Sanda showed that these angles could be determined through ''mixing-induced'' *CP* asymmetries, which arise in decays of neutral B mesons [8]. The most prominent decay is $B_d\to J/\psi K_S$, where the angle β can be obtained with essentially no theoretical uncertainty. Similarly, the angle α could be determined from $B_d\to\pi^+\pi^-$. Unfortunately, it was found later that this determination is not theoretically clean because of penguin contributions, leading to considerable hadronic uncertainties. These could be overcome by measuring all $B\to\pi\pi$ decays, in particular $B_d\to\pi^0\pi^0$ [9]. However, this mode is extremely difficult, if not impossible, to measure. The situation of the angle γ seemed even worse.

Since then, interesting new methods to extract this angle with few theoretical uncertainties were devised. For instance, it was shown that γ could be determined through the measurement of six $B^{\pm}\to K^{\pm}D$ decay rates [10]. To this end, the *CP* eigenstate

$$|D_+^0\rangle=\frac{1}{\sqrt{2}}(|D^0\rangle+|\overline{D^0}\rangle) \tag{1}$$

of the neutral D-meson system is employed, allowing the derivation of amplitude triangle relations. Unfortunately, the corresponding triangles in the complex plane, which are fixed through the magnitudes of the $B^{\pm}\to K^{\pm}D$ decay amplitudes, turned out to be highly stretched, and are, from an experimental point of view, not very useful to determine γ. Further difficulties were pointed out in Ref. [11]. As an alternative, the decays $B_d\to K^{*0}D$ were proposed [12] because the triangles are more equilateral. But all sides are small because of various suppression mechanisms. In another paper, the triangle approach to extract γ was also extended to the B_c system by Masetti [13].

Another road towards the extraction of γ, which will not be touched here, is provided by SU(3) relations between $B\to\pi K$, $\pi\pi$ decay amplitudes [14]. Although this approach is not theoretically clean, in contrast to the $B\to KD$ strategies using pure ''tree'' decays, it is more promising from an experimental point of view. In the context of the $B\to\pi K$ modes, it was pointed out that nontrivial bounds on γ could be obtained [15]. Also here, it was noted later that other decays than the original ones may provide more powerful bounds on γ [16]. Many recent papers review and extend the situation [17].

A comment on the implications of these different methods might be in order. As the $B\to KD$ triangle approaches rely on pure ''tree'' decays, i.e., do not involve any flavor-changing neutral-current (FCNC) processes, it is expected that they are not affected significantly by new physics (unless it affects D^0-$\overline{D^0}$ mixing) and probe indeed the angle γ as defined in the standard model. On the other hand, the $B\to\pi K$ methods are strongly sensitive to penguin, i.e., loop diagrams [18]. Since these can be influenced by new physics, the thus determined value of γ may be different from the standard model expectation. Consequently, a comparison of the values of γ obtained from pure ''tree'' decays and penguin-dominated modes would be a good way to search for new physics. Moreover, the values for γ could be compared with the usual fits of the unitarity triangle [19].

With the advent of hadronic b facilities, it becomes possible to produce both B_s and B_c mesons in large numbers. One might therefore ask to what extent these particles are

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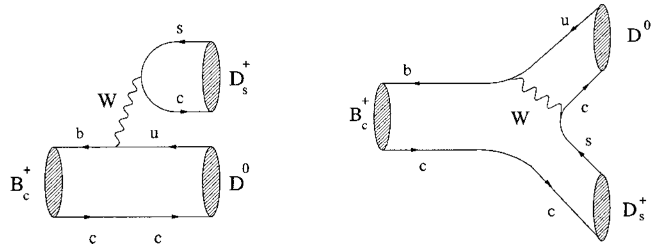

FIG. 1. Feynman diagrams contributing to the decay $B_c^+ \to D_s^+ D^0$.

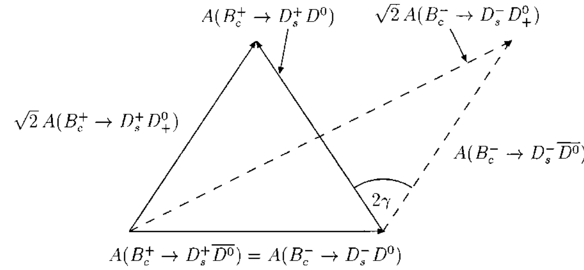

FIG. 3. The extraction of γ from $B_c^\pm \to D_s^\pm \{D^0, \overline{D^0}, D_+^0\}$ decays.

interesting for testing the standard model and, in particular, for studies of CP violation. In the case of B_s decays, there are already promising strategies [20]. Despite the early studies [13] of CP violation in nonleptonic B_c decays and other more recent work [21–23], no particular attention to the B_c system has emerged so far.

In this paper, we show that B_c mesons could indeed play an important role for the exploration of CP violation. In particular, the B_c counterpart of the $B^\pm \to K^\pm D$ triangle approach proposed in [10] could be well suited to extract the CKM angle γ. The corresponding B_c decays are $B_c^\pm \to D_s^\pm \{D^0, \overline{D^0}, D_+^0\}$, where the CP eigenstate D_+^0 introduced in Eq. (1) allows us to write the following amplitude relations:

$$\sqrt{2} A(B_c^+ \to D_s^+ D_+^0) = A(B_c^+ \to D_s^+ D^0) + A(B_c^+ \to D_s^+ \overline{D^0}), \tag{2}$$

$$\sqrt{2} A(B_c^- \to D_s^- D_+^0) = A(B_c^- \to D_s^- \overline{D^0}) + A(B_c^- \to D_s^- D^0). \tag{3}$$

The quark diagrams for these decays are shown in Figs. 1 and 2, where our main point can be seen: the amplitude with the rather small CKM matrix element V_{ub} is not color suppressed, while the larger element V_{cb} comes with a color-suppression factor. Therefore, the two amplitudes are similar in size. In contrast to this favorable situation, in the decays $B^\pm \to K^\pm \{D^0, \overline{D^0}, D_+^0\}$, the matrix element V_{ub} comes with the color suppression factor, resulting in a very stretched triangle, while in the decays $B_d \to K^{*0} \{D^0, \overline{D^0}, D_+^0\}$, all amplitudes are color suppressed.

Taking into account that $B_c^+ \to D_s^+ \overline{D^0}$ and $B_c^+ \to D_s^+ D^0$ receive only contributions from tree-diagram-like topologies because of the particular flavor structure of the underlying quark-decay processes, and that only the $\overline{b} \to \overline{u}$ transitions in Fig. 1 involve a CP-violating weak phase (γ) in the Wolfenstein parametrization of the CKM matrix [24], we obtain

$$A(B_c^+ \to D_s^+ \overline{D^0}) = A(B_c^- \to D_s^- D^0), \tag{4}$$

$$A(B_c^+ \to D_s^+ D^0) = e^{i2\gamma} A(B_c^- \to D_s^- \overline{D^0}). \tag{5}$$

Whereas Eq. (4) allows us to fix the relative orientation of the two triangles described by the amplitude relations (2) and (3), (5) allows us to determine the CKM angle γ, as is illustrated in Fig. 3. Since Eqs. (4) and (5) are exact in the standard model, this is theoretically clean. The method is completely analogous to the $B^\pm \to K^\pm D$ strategy [10]. However, as we have already noted, the advantage of the B_c decays is that all sides of the triangles in Fig. 3 are expected to be of comparable length:

$$\left| \frac{A(B_c^+ \to D_s^+ D^0)}{A(B_c^+ \to D_s^+ \overline{D^0})} \right| = \left| \frac{A(B_c^- \to D_s^- \overline{D^0})}{A(B_c^- \to D_s^- D^0)} \right| = \left| \frac{R_b (T_c + C_c)}{\tilde{C}_c + \tilde{A}_c} \right| = \mathcal{O}(1). \tag{6}$$

Here T_c and C_c denote the color-allowed and color-suppressed topologies in Fig. 1, $\tilde{C}_c$ and $\tilde{A}_c$ describe the color-suppressed and annihilation topologies in Fig. 2, and

$$R_b \equiv \frac{1}{\lambda} \left(1 - \frac{\lambda^2}{2} \right) \left| \frac{V_{ub}}{V_{cb}} \right| = 0.41 \pm 0.07, \quad \text{with } \lambda \equiv |V_{us}| = 0.22. \tag{7}$$

In contrast, the corresponding ratio for $B^\pm \to K^\pm D$ [10] is

$$\left| \frac{A(B^+ \to K^+ D^0)}{A(B^+ \to K^+ \overline{D^0})} \right| = \left| \frac{A(B^- \to K^- \overline{D^0})}{A(B^- \to K^- D^0)} \right| = \left| \frac{R_b (\tilde{C}_u + \tilde{A}_u)}{T_u + C_u} \right| = \mathcal{O}(0.1), \tag{8}$$

resulting in the unfortunate situation, where the sides of the amplitude triangles involving γ are strongly suppressed with respect to the remaining ones. A similar situation arises in the decays $B_c^\pm \to D^\pm \{D^0, \overline{D^0}, D_+^0\}$, obtained from the $B_c^\pm \to D_s^\pm \{D^0, \overline{D^0}, D_+^0\}$ channels by interchanging all down and strange quarks (U spin). These modes satisfy the amplitude relations

$$\sqrt{2} A(B_c^+ \to D^+ D_+^0) = A(B_c^+ \to D^+ D^0) + A(B_c^+ \to D^+ \overline{D^0}), \tag{9}$$

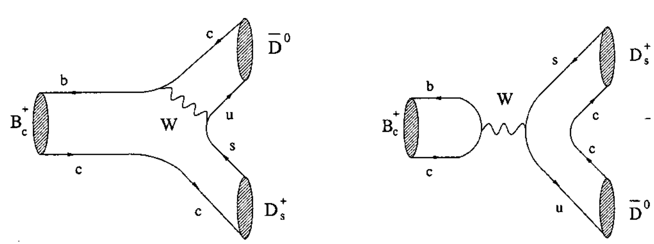

FIG. 2. Feynman diagrams contributing to the decay $B_c^+ \to D_s^+ \overline{D^0}$.

$$\sqrt{2}A(B_c^- \to D^- D_+^0) = A(B_c^- \to D^- \overline{D^0}) + A(B_c^- \to D^- D^0), \tag{10}$$

as well as

$$A(B_c^+ \to D^+ \overline{D^0}) = A(B_c^- \to D^- D^0),$$

$$A(B_c^+ \to D^+ D^0) = e^{i2\gamma} A(B_c^- \to D^- \overline{D^0}). \tag{11}$$

Because of CKM factors different from the $B_c^\pm \to D_s^\pm D$ case, we obtain

$$\left|\frac{A(B_c^+ \to D^+ D^0)}{A(B_c^+ \to D^+ \overline{D^0})}\right| = \left|\frac{A(B_c^- \to D^- \overline{D^0})}{A(B_c^- \to D^- D^0)}\right| = \lambda^2 \left|\frac{R_b(T_c' + C_c')}{\tilde{C}_c' + \tilde{A}_c'}\right| = \mathcal{O}(0.1), \tag{12}$$

and arrive at triangles of the same shape as in the $B^\pm \to K^\pm D$ approach. The decays $B_d \to K^{*0} D$ [12], whose amplitudes are all color suppressed and proportional to $\lambda^3(R_b)$, obviously have no analogue in the B_c system.

As was pointed out in [11], the small amplitude ratio (8) leads to another experimental problem: if the D^0 meson of the suppressed decay $B^+ \to K^+ D^0$ is tagged through the Cabibbo-favored mode $D^0 \to \pi^+ K^-$, there are large interference effects of $\mathcal{O}(1)$ with the color-allowed mode $B^+ \to K^+ \overline{D^0}[\to \pi^+ K^-]$, where the decay of the $\overline{D^0}$-meson is doubly Cabibbo-suppressed; indeed, all hadronic tags of the D^0 are affected in a similar way. In order to overcome these problems, it was proposed in [11] to use the decay chains

$$B^+ \to K^+ D^0[\to f_i], \quad B^+ \to K^+ \overline{D^0}[\to f_i], \tag{13}$$

where f_i denotes doubly Cabibbo-suppressed (Cabibbo-favored) non-*CP* modes of the $\overline{D^0}(D^0)$, for instance, $f_i = \pi^+ K^-$ or $\pi^+ \pi^0 K^-$. If two different final states f_i are considered, γ can be extracted. Advantages and problems of this approach are discussed in Ref. [6].

Because of Eq. (12), it is obvious that the $B_c^\pm \to D^\pm D$ strategy is affected by similar interference problems, i.e., we expect amplitudes of the same order of magnitude for the decay chains $B_c^+ \to D^+ D^0[\to \pi^+ K^-]$ and $B_c^+ \to D^+ \overline{D^0}[\to \pi^+ K^-]$. In order to extract γ, we could employ the same idea as in [11]. However, in the case of the B_c system, an alternative is provided by the following *U*-spin relations:

$$A(B_c^+ \to D^+ D^0) = -\lambda/(1-\lambda^2/2) A(B_c^+ \to D_s^+ D^0), \tag{14}$$

$$A(B_c^+ \to D^+ \overline{D^0}) = (1-\lambda^2/2)/\lambda A(B_c^+ \to D_s^+ \overline{D^0}). \tag{15}$$

Since the decay amplitudes on the right-hand sides of these equations are of the same order of magnitude, as we have seen in Eq. (6), the interference effects due to $D^0, \overline{D^0} \to \pi^\pm K^\mp$ are practically unimportant in their measurement and in the associated $B_c^\pm \to D_s^\pm \{D^0, \overline{D^0}, D_+^0\}$ strategy to determine γ. Consequently, this is the preferred B_c approach to extract γ. Nevertheless, the Cabibbo-enhanced decay $B_c^+ \to D^+ \overline{D^0}$ plays an important role to increase the statistics for the measurement of the basis of the triangles shown in Fig. 3 with the help of Eq. (15). Needless to note, similar strategies are provided, if the $D_{(s)}^\pm$ mesons are replaced by $D_{(s)}^{*\pm}$ mesons or higher resonances, which may have advantages for certain detector configurations [25].

At the CERN Large Hadron Collider (LHC), one expects a huge number of B_c mesons, about 10^{10} untriggered B_c's per year of running [26]. The branching ratios for the color-suppressed B_c decays were already estimated in the literature, however, with conflicting results [22,23]. The following values seem reasonable:

$$\mathcal{B}(B_c^+ \to D_s^+ \overline{D^0}) \approx 10^{-5} - 10^{-6} \tag{16}$$

$$\mathcal{B}(B_c^+ \to D_s^+ D^0) \approx 10^{-5}. \tag{17}$$

The first numbers for the color-suppressed modes correspond to the range given in [23,22], while the second one for the color-allowed channels is an estimate based on the results for decays with a similar dynamics given in these papers. It is seen that the rates are indeed comparable. Moreover, we expect

$$\mathcal{B}(B_c^+ \to D^+ \overline{D^0}) \approx 10^{-4} - 10^{-5}, \tag{18}$$

allowing the measurement of Eq. (16) with the help of Eq. (15). The predictions for the color-suppressed $B_c^+ \to D_s^{*+} \overline{D^0}$ and $B_c^+ \to D^{*+} \overline{D^0}$ modes in [22] and [23] are in better agreement:

$$\mathcal{B}(B_c^+ \to D_s^{*+} \overline{D^0}) = 4 \times 10^{-6},$$

$$\mathcal{B}(B_c^+ \to D^{*+} \overline{D^0}) = 7 \times 10^{-5}; \tag{19}$$

for the decay $B_c^+ \to D_s^{*+} D^0$, we expect a branching ratio at the 10^{-5} level.

The feasibility of the methods discussed above depends of course on the experimental situation and the relevant branching ratios. If we assume those of the final D mesons to be 5% and an overall efficiency of 10%, we arrive at around 20 events per year at LHC. This crude estimate indicates that the B_c system may well contribute to our understanding of *CP* violation.

In this Brief Report, we have shown that decays of B_c mesons appear to be ideally suited for determining the angle γ from triangle relations. The well known disadvantages of this approach arising in B_u and B_d decays, namely small amplitudes, are absent. Provided there are no serious experimental problems related to the analysis of the corresponding B_c decays, this approach should be very interesting for the B physics program at future hadron colliders.

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