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Possibility of measuring the CP-violation γ-parameter in decays of Ξ_{bc} baryons

V.V. Kiselev, O.P. Yushchenko

Russian State Research Center "Institute for High Energy Physics", Protvino, Moscow Region, 142281 Russia

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Abstract

The model-independent method based on the triangle ideology is implemented to extract the CKM-matrix angle γ in the decays of doubly heavy baryons containing the charmed and beauty quarks. We analyze a color structure of diagrams and conditions for reconstructing two reference-triangles by tagging the flavor and CP eigenstates of $D^0 \leftrightarrow \overline{D}^0$ mesons in the fixed exclusive channels. The characteristic branching ratios are evaluated in the framework of a potential model setting a parametric dependence on the hadronic matrix elements for the decay rates.

1. Introduction

The current success in the experimental study of decays with the CP-violation in the gold-plated mode of neutral B-meson by the BaBar and Belle Collaborations [1] allows one to extract the CKM-matrix angle β in the unitarity triangle by the model-independent method. The intensive efforts are intended in the physical programs on the B and B_s mesons at the hadron colliders both the active Tevatron [2] and prospective LHC. Due to the relatively high cross-sections the doubly heavy hadrons such as the B_c meson and baryons Ξ_{bc}, Ω_{bc} and Ξ_{cc}, Ω_{bc} would be copiously produced at such the machines [3,4]. In addition to the indirect or model-dependent measurements of unitarity triangle [5], there is an intriguing opportunity to extract the angle γ in the model-independent way using the strategy of reference triangles [6] in the decays of doubly heavy hadrons. This ideology for the study of CP-violation in B_c decays was originally offered by Masetti [7] and investigated by Fleischer and Wyler [8]. In this Letter we extend the method to study the decays of doubly heavy baryons containing the charmed and beauty quarks.

To begin, we mention the necessary conditions for extracting the CP-violation effects in the model-independent way.

E-mail address: kiselev@th1.ihep.su (V.V. Kiselev).

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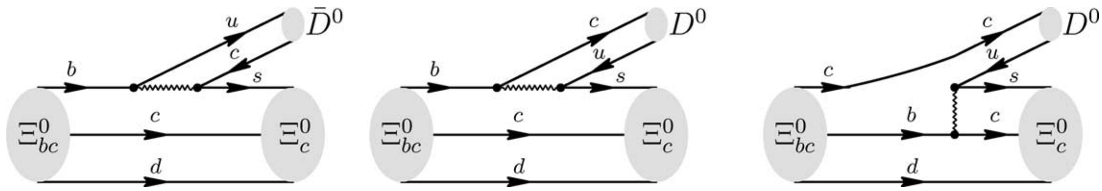

Fig. 1. The diagrams of b-quark decay contributing to the weak transitions $\Xi^0_{bc} \to D^0 \Xi^0_c$ and $\Xi^0_{bc} \to \overline{D}^0 \Xi^0_c$.

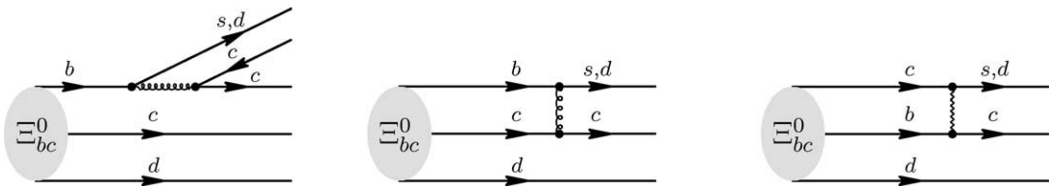

Fig. 2. The penguins and weak scattering diagrams.

1. Interference. The measured quantities have to involve the amplitudes including both the CP-odd and CP-even phases;
2. Exclusive channels. The hadronic final state has to be fixed in order to isolate the definite matrix elements of CKM matrix, which can exclude the interference of two CP-odd phases with indefinite CP-even phases due to strong interactions at both levels of the quark structure and the interactions in the final state;
3. Oscillations. The definite involvement of the CP-even phase is ensured by the oscillations taking place in the systems of neutral B or D mesons, wherein the CP-breaking effects can be systematically implemented;
4. Tagging. Once the oscillations are involved, the tagging of both the flavor and CP eigenstates is necessary for the complete procedure.

The gold-plated modes in the decays of neutral B mesons involve the oscillations of mesons themselves and, hence, they require the time-dependent measurements. In contrast, the decays of doubly heavy hadrons such as the B_c meson and Ξ_{bc} baryons with the neutral D^0 or $\overline{D}^0$ meson in the final state do not require the time-dependent measurements. The triangle ideology is based on the direct determination of absolute values for the set of six decays: the decays of baryon in the tagged D^0 meson, the tagged $\overline{D}^0$ meson, the tagged CP-even state, and those of the anti-baryon. To illustrate, let us consider the decays of

$$\Xi^0_{bc} \to D^0 \Xi^0_c, \quad \text{and} \quad \Xi^0_{bc} \to \overline{D}^0 \Xi^0_c.$$

The corresponding diagrams with the decay of b-quark are shown in Fig. 1. We stress that two diagrams of the baryon decay to D^0 has the additional negative sign caused by the Pauli interference of two charmed quarks, while the color factors is analyzed in the next section.

The exclusive modes make the penguin terms to be excluded, since the penguins add an even number of charmed quarks, i.e., two or zero, while the final state contains two charmed quarks including one from the b decay and one from the initial state. By the same reason the diagrams with the weak scattering of two constituents, i.e., the charmed and beauty quarks in the Ξ^0_{bc} baryon, are also excluded for the given final state (see Fig. 2).

The weak scattering of b quark off the charmed quark in the initial state can contribute in the next order in α_s as shown in Fig. 3. Nevertheless, we see that such the diagrams have the same weak-interaction structure as at the tree level. Therefore, they do not break the symmetries under consideration. The magnitude of α_s-correction to the absolute values of corresponding decay widths is discussed in Section 2.

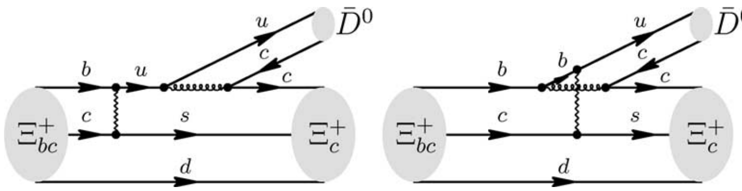

Fig. 3. The diagrams for the weak scattering of b and c quarks contributing to the transition $\Xi_{bc}^0 \to \overline{D}^0 \Xi_c^0$.

Thus, the CP-odd phases of decays under consideration are determined by the tree-level diagrams shown in Fig. 1. Therefore, we can write down the amplitudes in the following form:

$$\mathcal{A}\big(\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0\big) \stackrel{\text{def}}{=} \mathcal{A}_{\overline{D}} = V_{ub} V_{cs}^* \cdot \mathcal{M}_{\overline{D}}, \qquad \mathcal{A}\big(\Xi_{bc}^0 \to \Xi_c^0 D^0\big) \stackrel{\text{def}}{=} \mathcal{A}_D = V_{cb} V_{us}^* \cdot \mathcal{M}_D, \tag{1}$$

where $\mathcal{M}_{\overline{D},D}$ denote the CP-even factors depending on the dynamics of strong interactions. Using the definition of angle γ

$$\gamma \stackrel{\text{def}}{=} -\arg\left[\frac{V_{ub} V_{cs}^*}{V_{cb} V_{us}^*}\right],$$

for the CP-conjugated channels[1] we find

$$\mathcal{A}\big(\overline{\Xi}_{bc}^0 \to \overline{\Xi}_c^0 D^0\big) = e^{2i\gamma} \mathcal{A}_{\overline{D}}, \qquad \mathcal{A}\big(\overline{\Xi}_{bc}^0 \to \overline{\Xi}_c^0 \overline{D}^0\big) = \mathcal{A}_D. \tag{2}$$

We see that the corresponding widths for the decays to the flavor tagged modes coincide with the CP-conjugated ones. However, the story can be continued by using the definition of CP-eigenstates for the oscillating $D^0 \leftrightarrow \overline{D}^0$ system,[2]

$$D_{1,2} = \frac{1}{\sqrt{2}}\big(D^0 \pm \overline{D}^0\big),$$

so that we straightforwardly get

$$\sqrt{2}\,\mathcal{A}\big(\Xi_{bc}^0 \to \overline{\Xi}_c^0 D_1\big) \stackrel{\text{def}}{=} \sqrt{2}\,\mathcal{A}_{D_1} = \mathcal{A}_{\overline{D}} + \mathcal{A}_D, \tag{3}$$

$$\sqrt{2}\,\mathcal{A}\big(\overline{\Xi}_{bc}^0 \to \overline{\Xi}_c^0 D_1\big) \stackrel{\text{def}}{=} \sqrt{2}\,\mathcal{A}_{D_1}^{\text{CP}} = e^{2i\gamma} \mathcal{A}_{\overline{D}} + \mathcal{A}_D. \tag{4}$$

The complex numbers entering (3) and (4) establish two triangles with the definite angle 2γ between the vertex positions as shown in Fig. 4. Thus, due to the unitarity, the measurement of four absolute values

$$\begin{aligned} |\mathcal{A}_{\overline{D}}| &= \big|\mathcal{A}\big(\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0\big)\big|, \qquad & |\mathcal{A}_D| &= \big|\mathcal{A}\big(\Xi_{bc}^0 \to \Xi_c^0 D^0\big)\big|, \\ |\mathcal{A}_{D_1}| &= \big|\mathcal{A}\big(\Xi_{bc}^0 \to \Xi_c^0 D_1\big)\big|, \qquad & \big|\mathcal{A}_{D_1}^{\text{CP}}\big| &= \big|\mathcal{A}\big(\overline{\Xi}_{bc}^0 \to \overline{\Xi}_c^0 D_1\big)\big|, \end{aligned} \tag{5}$$

can constructively reproduce the angle γ in the model-independent way.

The above triangle-ideology can be implemented for the analogous decays to the excited states of charmed hyperons in the final state.

The residual theoretical challenge is to evaluate the characteristic widths or branching fractions. We address this problem and analyze the color structure of amplitudes. So, we find that the matrix elements under consideration

[1] For the sake of simplicity we put the overall phase of $\arg V_{cb} V_{us}^* = 0$, which corresponds to fixing the representation of the CKM matrix, e.g., by the Wolfenstein form [9].

[2] The suppressed effects of CP-violation in the oscillations of neutral D mesons are irrelevant here, and we can safely neglect them.

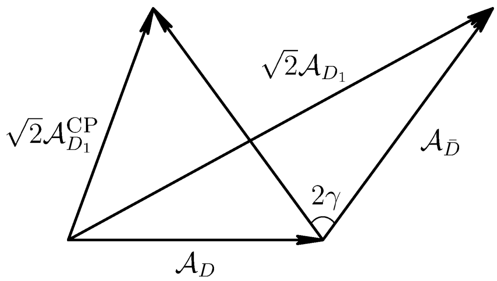

Fig. 4. The reference-triangles.

have the same magnitude of color suppression $\mathcal{A} \sim O(1/\sqrt{N_c})$, while the ratio of relevant CKM-matrix elements,

$$\left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \sim O(1)$$

with respect to the small parameter of Cabibbo angle, $\lambda = \sin\theta_C$, which one can easily find in the Wolfenstein parametrization

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - {\rm i}\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-{\rm i}\eta) & -A\lambda^2 & 1 \end{pmatrix}.$$

Thus, we expect that the sides of the reference-triangles are of the same order of magnitude, which makes the method to be a realistic way for extracting the angle γ.

In Section 2 we classify the diagrams for the decays of doubly heavy baryons $\Xi_{bc}^{0,+}$ and Ω_{bc}^0 by the color and weak-interaction structures. Section 3 is devoted to the numerical estimates in the framework of a potential model. The results are summarized in conclusion.

2. Color structures

Let us remind a general framework of the $1/N_c$-expansion. Its physical meaning at $N_c \to \infty$ quite reasonably implies that the quarks are bound by the gluon string, which is not broken by the quark–anti-quark pair creation. So, the excitations of the ground states are quasi-stable under the strong interactions producing the decays described by the $1/N_c$-suppressed terms. In this method we have got the following scaling rules of color structures:

1. The meson wavefunction

$$\Psi_M \sim \frac{1}{\sqrt{N_c}}\delta^i{}_j;$$

2. The baryon wavefunction

$$\Psi_B \sim \frac{1}{\sqrt{N_c!}}\epsilon_{i[1]\cdots i[N_c]};$$

3. The coupling constant

$$\alpha_s \sim \frac{1}{N_c};$$

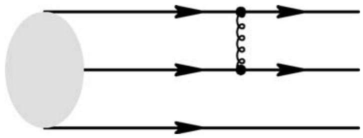

Fig. 5. The connection of baryon structure constant.

4. The Casimir operators

$$C_A = N_c, \qquad C_F = \frac{N_c^2 - 1}{2N_c} \sim O(N_c);$$

5. The Fierz relation for the generators of SU(N_c) group in the fundamental representation

$$t^{Ai}{}_j t^{Ak}{}_m = \frac{C_F}{N_c}\delta^i{}_m \delta^k{}_j - \frac{1}{N_c} t^{Ai}{}_m t^{Ak}{}_j;$$

6. The baryon structure constant

$$C_B = -\frac{N_c + 1}{2N_c} \sim O(1).$$

It gives the color factor emerging in the connection of two quark lines entering the baryon by the gluon line (see Fig. 5).

Next, the non-leptonic weak Lagrangian has a form typically given by the following term [10]:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{2\sqrt{2}} V_{cb}\big(\bar{b}^i \Gamma_\mu c_j\big) V_{us}^* \big(\bar{u}^k \Gamma^\mu s_l\big) C_\pm \big(\delta^i{}_j \delta^k{}_l \pm \delta^i{}_l \delta^k{}_j\big) + \cdots, \tag{6}$$

where $\Gamma_\mu = \gamma_\mu(1 - \gamma_5)$, and the Wilson coefficients

$$C_\pm \sim O(1)$$

in the $1/N_c$-expansion.

Then, we can proceed with the analysis of decays under consideration.

2.1. Ξ_{bc}^0

All three diagrams shown in Fig. 1 have the same order in $1/N_c$, i.e.,

$$\mathcal{A}_1 \sim \mathcal{A}_2 \sim \mathcal{A}_3 \sim \frac{1}{\sqrt{N_c}}.$$

More definitely we get the color factors

$$\mathcal{F}_1^c = \sqrt{N_c}\, a_2, \qquad \mathcal{F}_2^c = \sqrt{N_c}\, a_2, \qquad \mathcal{F}_3^c = \frac{C_-}{\sqrt{N_c}} = (a_1 - a_2)\frac{\sqrt{N_c}}{N_c - 1}, \tag{7}$$

where

$$a_1 = \frac{1}{2N_c}\big[C_+(N_c + 1) + C_-(N_c - 1)\big], \tag{8}$$

$$a_2 = \frac{1}{2N_c}\big[C_+(N_c + 1) - C_-(N_c - 1)\big]. \tag{9}$$

Thus, we have to calculate the three diagrams given above in the leading order in $1/N_c$.

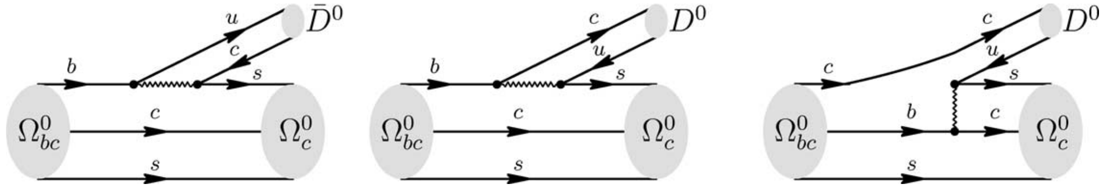

Fig. 6. The diagrams of b-quark decay contributing to the weak transitions $\Xi^0_{bc} \to D^0\Omega^0_c$ and $\Xi^0_{bc} \to \overline{D}^0\Omega^0_c$.

2.2. Ω^0_{bc}

The decay modes

$$\Omega^0_{bc} \to D^0\Omega^0_c, \quad \text{and} \quad \Omega^0_{bc} \to \overline{D}^0\Omega^0_c$$

are described by the diagrams shown in Fig. 6 similar to those of Fig. 1. The only difference is the replacement of d quark by the strange one, that should be taken into account by the anti-symmetrization of wavefunction in the final state, i.e., the baryon structure of Ω^0_c, which results in the vector-spin state of the doubly strange diquark. Then, the appropriate color factors are given in (7).

The diagrams for the decay modes

$$\Omega^0_{bc} \to D^0\Xi^0_c, \quad \text{and} \quad \Omega^0_{bc} \to \overline{D}^0\Xi^0_c$$

can be obtained from those of Fig. 6 by the replacement of weak currents $u \to s$ by $u \to d$ and $c \to s$ by $c \to d$. The triangle ideology is effective in the case under consideration too. The color factors are given by (7) again. However, the amplitude of $\Omega^0_{bc} \to \overline{D}^0\Xi^0_c$ is suppressed by the CKM-matrix factor of

$$\left|\frac{V_{ub}V^*_{cd}}{V_{cb}V^*_{ud}}\right| \sim O(\lambda^2),$$

which implies that the corresponding side of reference-triangle will be much less than another. In practice, the relatively large branching of decay to the D^0 meson should be measured with extremely high accuracy in order to make a sense in the reconstruction of the triangle with the relatively small side determined by the branching of decay to $\overline{D}^0$ meson.

However, with an expected event rate discussed below, in the nearest future there is no opportunity to observe the Ω triangles in practice.

2.3. Ξ^+_{bc}

The diagrams for the decay

$$\Xi^+_{bc} \to \overline{D}^0\Xi^+_c$$

are shown in Fig. 7, where the negative relative sign caused by the Pauli interference should be taken into account. The corresponding color factors are given by $\mathcal{F}^c_2$ and $\mathcal{F}^c_3$ in (7).

The consideration of decays into the D^0 meson is more complicated because of the weak scattering of constituent b and u quarks as shown in Fig. 8. We can easily find that the gluon emission from the other quark lines is suppressed by the color factor since such the exchange by the gluon leads to the baryon color-structure factor C_B in contrast to the C_F in the diagrams shown in Fig. 8. The spectator charmed quark cannot emit the virtual gluon, since the quark line should be on mass shell up to the small virtualities about the relative momentum of the quark inside the baryon.

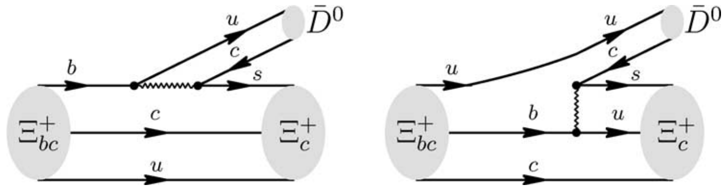

Fig. 7. The diagrams of b-quark decay contributing to the weak transition $\Xi_{bc}^+ \to \overline{D}^0 \Xi_c^+$.

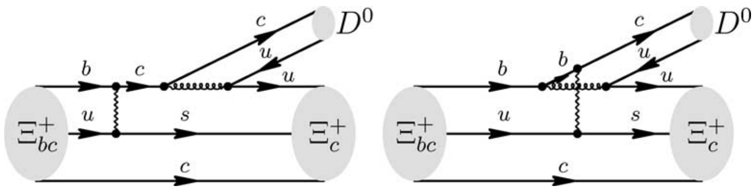

Fig. 8. The diagrams for the weak scattering of b and u quarks contributing to the transition $\Xi_{bc}^+ \to D^0 \Xi_c^+$.

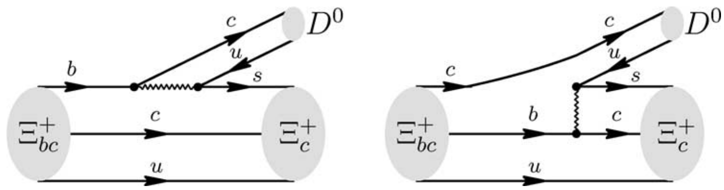

Fig. 9. The diagrams of b-quark decay contributing to the weak transition $\Xi_{bc}^+ \to D^0 \Xi_c^+$.

Further, the color factors for the diagrams in Fig. 8 have the form

$$\mathcal{F}^c \sim \frac{1}{\sqrt{N_c}}.$$

Thus, these factors are of the same order of magnitude as for the decay amplitudes shown in Fig. 9.

Finally, in this section we have analyzed the color and weak-interaction structures of decay amplitudes and isolate those of the largest magnitude, while an illustrative numerical estimate is presented in the next section.

3. Numerical estimates

In this section we formulate the framework of a potential model, which allows us to evaluate the characteristic widths and branching ratios for the modes under study.

Let us consider the decay of $\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0$. So, we define the doubly heavy baryon state in its rest frame by the following form:

$$\begin{aligned} \left|\Xi_{bc}^0\right\rangle = \sqrt{2M_1} \int \frac{\mathrm{d}^3k}{(2\pi)^3} \frac{\mathrm{d}^3q}{(2\pi)^3} \Psi_{bc}(\boldsymbol{k}) \Psi_d(\boldsymbol{q}) \frac{1}{\sqrt{N_c!}} \epsilon^{ijk} \left(b^{\mathrm{T}}(v_1) \mathrm{C} \frac{\gamma_5}{\sqrt{2}} c(v_1) \right) d(v_1) \\ \times a_i^\dagger[b](\boldsymbol{k}) a_j^\dagger[c](-\boldsymbol{k}) a_k^\dagger[d](\boldsymbol{q}) |0\rangle, \end{aligned} \tag{10}$$

where C is the charge-conjugation matrix, and we have introduced the following notations:

- the relativistic normalization-factor $\sqrt{2M_1}$ with M_1 being the baryon mass in the initial state;

- the wavefunction Ψ given by two factors of the doubly heavy diquark and the d quark;
- the color wavefunction determined by $\epsilon^{ijk}/\sqrt{N_c!}$;
- the spin wavefunction of scalar doubly heavy diquark as determined by the spinor factor $\gamma_5/\sqrt{2}$;
- the quark spinors depending on the four-velocity of the baryon, v_1, as normalized by the condition of sum over the polarization states, say,

$$\sum b(v_1)\bar{b}(v_1) = \frac{1}{2}(1+\not{v}_1);$$

- $a^\dagger$ denoting the creation operator marked by the flavor, color and momentum in an appropriate way.

In (10), we use the momentum-space wavefunction in the form of

$$\Psi\left(k^2\right) = \left(\frac{8\pi}{\omega^2}\right)^{3/4} \exp\left[\frac{k^2}{\omega^2}\right],$$

where the four-vector satisfies the condition

$$k \cdot v_1 = 0.$$

The model parameter ω is related with the wavefunction $\tilde{\Psi}(0)$ at the origin in the configuration space. Such the quantities were calculated by solving the Schrödinger equation with the static potential as described in [12], so that

$$\tilde{\Psi}_{bc}(0) = 0.73\ \mathrm{GeV}^{3/2}, \qquad \tilde{\Psi}_d(0) = 0.53\ \mathrm{GeV}^{3/2},$$

while for the Ξ_c^0 baryon we take

$$\tilde{\Psi}_{cs}(0) = 0.61\ \mathrm{GeV}^{3/2}, \qquad \tilde{\Psi}_d(0) = 0.53\ \mathrm{GeV}^{3/2}.$$

We will see that for the mode under consideration the absolute values of above parameters are not so critical, while their ratios are important.

Then the matrix element is equal to

$$\mathcal{A}_{\overline{D}} = \frac{G_F}{\sqrt{2}} V_{ub}^* V_{cs} \sqrt{M_1 M_2 M_D}\, \tilde{\Psi}_D(0) \sqrt{N_c}\, a_2 \cdot \mathcal{T} \cdot \mathcal{O} \cdot \bar{u}(v_2) u(v_1), \tag{11}$$

where the mass and wavefunction factors as well as the spinors and four-velocities are transparently denoted, while $\mathcal{T}$ is given by the spin structure of the matrix element

$$\mathcal{T} = \frac{1}{8} \mathrm{Tr}\left[(1+\not{v}_1)(1+\not{v}_2)\gamma_\mu(1-\gamma_5)\gamma_5(1+\not{v}_D)\gamma^\mu(1-\gamma_5)\right],$$

and $\mathcal{O}$ represents the overlapping of wavefunctions, which can be calculated in the model specified. So, it is presented by the product of ξ factors

$$\mathcal{O} = \xi_{bc\to cs}(y) \cdot \xi_d(y),$$

where the diquark transition is determined by

$$\xi_{bc\to cs} = \frac{2\omega_{bc}\omega_{cs}}{\omega_{bc}^2 + \omega_{cs}^2} \sqrt{\frac{2\omega_{bc}\omega_{cs}}{\omega_{cs}^2 + y^2\omega_{bc}^2}}\ \exp\left[-\frac{\tilde{m}^2(y^2-1)}{\omega_{cs}^2 + y^2\omega_{bc}^2}\right], \tag{12}$$

with $y = v_1 \cdot v_2$ and

$$\tilde{m} = m_c \frac{M_1 + m_s - m_b}{m_c + m_s} \approx m_c + O(m_{s,d}/m_c).$$

In the given kinematics the product of four-velocities is fixed by

$$y = \frac{M_1^2 + M_2^2 - M_D^2}{2M_1M_2}.$$

The factor of $\xi_d(y)$ has the form similar to (12) under the appropriate substitutions for the values of ω as well as for $\tilde{m} \to m_d$ [11].

Having written down Eq. (11), we have neglected the α_s-corrections following from the diagrams shown in Fig. 3. This approximation is theoretically sound. Indeed, the gluon virtuality is determined by the expression

$$k_g^2 = m_c^2(v_2 + v_D)^2 = m_c^2 \frac{M_1^2 - (M_2 - M_D)^2}{2M_2M_D} \approx (m_b + m_c)^2 + O(m_{s,d}/m_{c,b}) \gg \Lambda_{\mathrm{QCD}}^2.$$

The suppression factor of appropriate diagrams is given by

$$\mathcal{S} \sim |\tilde{\Psi}(0)|^2 \frac{\alpha_s(k_g^2)}{k_g^2} \frac{N_c}{\Delta E_Q},$$

where

$$|\tilde{\Psi}(0)|^2 \sim \Lambda_{\mathrm{QCD}}^3$$

is the characteristic value of wavefunction, and the virtuality of heavy quark line connected to the virtual gluon is of the order of

$$\Delta E_Q \sim m_{c,b}.$$

Therefore,

$$\mathcal{S} \sim \frac{\Lambda_{\mathrm{QCD}}^3}{m_{c,b}^3} \frac{1}{\ln m_{c,b}/\Lambda_{\mathrm{QCD}}} \ll 1.$$

Similar relations can be found, if we consider the value of α_s-correction due to the weak scattering shown in Fig. 8. One can easily find that the corresponding suppression is given by

$$\tilde{\mathcal{S}} \sim \frac{\Lambda_{\mathrm{QCD}}}{m_{c,b}} \ll 1,$$

where we have suggested the constituent mass of light quark

$$m_{u,d} \sim \Lambda_{\mathrm{QCD}}.$$

Therefore, the above α_s-corrections can be neglected to the leading order in the $1/m_Q$-expansion.

Further,

$$\mathcal{T} = 2(1+y)\frac{M_1 - M_2}{M_D},$$

and we can get the matrix element squared

$$|\mathcal{A}_{\overline{D}}|^2 = \frac{G_F^2}{2}\left|V_{ub}^2 V_{cs}^2\right| M_1 M_2 (M_1 - M_2)^2 (1+y)^3 f_D^2 \cdot \mathcal{O}^2 \cdot (N_c a_2)^2, \tag{13}$$

where we have expressed the wavefunction of D meson in terms of its effective leptonic constant f_D,

$$f_D = 2\sqrt{\frac{3}{M_D}}\,\tilde{\Psi}(0).$$

Then, the width is given by

$$\Gamma\big[\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0\big] = \frac{|\boldsymbol{k}_D|}{16\pi M_1^2} |\mathcal{A}_{\overline{D}}|^2,$$

where $\boldsymbol{k}_D$ is the momentum of D meson in the Ξ_{bc}^0 rest-frame.

Numerically, at $M_1 \approx 6.9$ GeV [13,14] we find

$$\Gamma\big[\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0\big] \approx 1.3 \times 10^{-6}\ \text{ps}^{-1} \times \left| \frac{V_{ub}^2}{0.003^2} \frac{V_{cs}^2}{0.975^2} \right| \frac{f_D^2}{(0.222\ \text{GeV})^2} \cdot \mathcal{O}^2 \cdot \frac{(N_c a_2)^2}{1}. \tag{14}$$

Putting [4,15]

$$\tau\big[\Xi_{bc}^0\big] = 0.27\ \text{ps},$$

we get

$$\mathcal{B}\big[\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0\big] \approx 3.6 \times 10^{-6} \times \left| \frac{V_{ub}^2}{0.003^2} \frac{V_{cs}^2}{0.975^2} \right| \frac{f_D^2}{(0.22\ \text{GeV})^2} \cdot \mathcal{O}^2 \cdot \frac{(N_c a_2)^2}{1}. \tag{15}$$

The calculation of overlap between the wavefunctions is model-dependent, though one can expect that $\mathcal{O} \sim 1$. In the framework of potential model described we get

$$\mathcal{O} \approx 0.44,$$

which gives our final estimate

$$\mathcal{B}\big[\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0\big] \approx 0.7 \times 10^{-6} \times \left| \frac{V_{ub}^2}{0.003^2} \frac{V_{cs}^2}{0.975^2} \right| \frac{f_D^2}{(0.22\ \text{GeV})^2} \cdot \frac{\mathcal{O}^2}{0.2} \cdot \frac{(N_c a_2)^2}{1}. \tag{16}$$

Therefore, we could expect that the other branching ratios are of the same order of magnitude.

4. Conclusion

In this Letter we have extended the reference-triangle ideology to the model-independent extraction of CKM-matrix angle γ from the set of branching ratios of doubly heavy baryons exclusively decaying to the neutral D mesons. Tagging the flavor and CP-eigenstates of such the D mesons allows one to avoid the uncertainties caused by the QCD dynamics of quarks.

We have estimated the characteristic branching ratios in the framework of a potential model, which yields, for example,

$$\mathcal{B}\big[\Xi_{bc}^0 \to \Xi_c^0 \overline{D}^0\big] \approx 0.7 \times 10^{-6}.$$

Accepting the above value, we can estimate the rate of events at the LHC collider in the experiment LHCB or in the BTeV facility at FNAL. So, the production cross section yields the characteristic value of about 10^9 doubly charmed baryons per year [2]. Next, the estimated branching rations for the charmed strange baryons are measured for Ξ_c^+, so that the detection of charged particles in the final state would cover about 50% of decay events with Ξ_c^+, which we accept for the optimistic estimates. The efficiency of observing the neutral charmed meson crucially depends on the possibility for detecting the neutral kaons and pions. So, removing the neutral kaons and pions could kill the opportunity offered in the present Letter. We consider the optimistic case with the required detection at work, which gives the efficiency for observing the D^0 decay at the level of 25%. Therefore, putting the vertex reconstruction efficiency equal to 10%, we can expect the observation of about $10^9 \times 0.7 \times 10^{-6} \times 5 \times 10^{-1} \times 2.5 \times 10^{-1} \times 10^{-1} \approx 11$ events per year. However, the situation is less optimistic for the detection of CP-eigenstates of D^0. Indeed, the CP-even mode with the $\pi^+\pi^-$ or K^+K^- final states covers only a 5×10^{-3} fraction of D^0 decays, which makes the observation unreachable. The CP-odd events with $K_S\pi^0$ can be detected with the branching fraction about 2.5×10^{-2}, which downs the rate to 1 event per year. Thus, the reconstruction of reference triangle after 10 years of data taking would give, at least, the 30% accuracy for the characteristic triangle side, which makes the extraction of angle γ rather academic exercise in the method offered.

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