Direct CP violation in internal W -emission dominated baryonic B decays

Y. K. Hsiao^{1,a}, Shang-Yuu Tsai^{1,b}, Eduardo Rodrigues^{2,c}

¹ School of Physics and Information Engineering, Shanxi Normal University, Linfen 041004, China

² Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK

Received: 14 March 2020 / Accepted: 9 June 2020 / Published online: 23 June 2020

© The Author(s) 2020

Abstract The observation of CP violation has been experimentally verified in numerous B decays but is yet to be confirmed in final states with half-spin particles. We focus our attention on baryonic B -meson decays mediated dominantly through internal W -emission processes and show that they are promising processes to observe for the first time the CP violating effects in B decays to final states with half-spin particles. Specifically, we study the $\bar{B}^0 \rightarrow p\bar{p}\pi^0(\rho^0)$ and $\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-$ decays. We obtain $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0) = (5.0 \pm 2.1) \times 10^{-7}$, in agreement with current data, and $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\rho^0) \simeq \mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0)/3$. Furthermore, we find $\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\pi^0, p\bar{p}\rho^0, p\bar{p}\pi^+\pi^-) = (-16.8 \pm 5.4, -12.6 \pm 3.0, -11.4 \pm 1.9)\%$. With measured branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0, p\bar{p}\pi^+\pi^-) \sim \mathcal{O}(10^{-6})$, we point out that $\mathcal{A}_{CP} \sim -(10 - 20)\%$ can be new observables for CP violation, accessible to the Belle II and/or LHCb experiments.

1 Introduction

The investigation of CP violation (CPV) has been one of the most important tasks in hadron weak decays. In the Standard Model (SM), CPV arises from a unique phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix; however, it is insufficient to explain the matter and antimatter asymmetry of the Universe. To try and shed light on solving the above puzzle, a diverse set of observations related to CPV is necessary. So far, direct CP violation has been observed in B and D decays [1,2]. With $Re(\epsilon'/\epsilon)$, it is also found in kaon decays [3]. Although the decays involving half-spin particles offer an alternative route, evidence for CP violation is not richly provided [4,5].

Baryonic B decays can be an important stage to investigate CPV within the SM and beyond. With $M^{(*)}$ denoting a pseudoscalar (vector) meson such as $K^{(*)}$, π , ρ , $D^{(*)}$, the $B \rightarrow p\bar{p}M^{(*)}$ decays have been carefully studied by the B factories and the LHCb experiment [5–11]. Experimental information includes measurements of branching fractions, angular distribution asymmetries, polarization of vector mesons in $B \rightarrow p\bar{p}K^*$, Dalitz plot information, and $p\bar{p}(M^{(*)}p)$ invariant mass spectra. This helps to improve the theoretical understanding of the di-baryon production in $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'M$ [12–16], such that the data can be well interpreted. Predictions are confirmed by recent measurements. For example, one obtains $\mathcal{B}(\bar{B}_s^0 \rightarrow p\bar{\Lambda}K^- + \Lambda\bar{p}K^+) = (5.1 \pm 1.1) \times 10^{-6}$ [17], in excellent agreement with the value of $(5.46 \pm 0.61 \pm 0.57 \pm 0.50 \pm 0.32) \times 10^{-6}$ measured by LHCb [18]. Moreover, the theoretical extension to four-body decays allows to interpret $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-)$ [19–21]. The same can be said for CP asymmetries.

In this report we focus our attention on the baryonic B -meson decays mediated dominantly through the internal W -emission diagrams. Although the internal W -emission decays are regarded as suppressed processes, the measured branching fractions of the baryonic B decays

$$\begin{aligned}\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0) &= (5.0 \pm 1.8 \pm 0.6) \times 10^{-7}, \\ \mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-) &= (2.7 \pm 0.1 \pm 0.1 \pm 0.2) \times 10^{-6},\end{aligned}\quad (1)$$

are not small [19,22], which make these modes an ideal place to observe for the first time CP violation in B decays to final states with half-spin particles. Therefore, we will study the branching fractions for the decays of $\bar{B}^0 \rightarrow p\bar{p}\pi^0(\rho^0)$, $p\bar{p}\pi^+\pi^-$, and predict their direct CP violating asymmetries.

^a e-mail: yukuohsiao@gmail.com

^b e-mail: shangyuu@gmail.com (corresponding author)

^c e-mail: eduardo.rodrigues@cern.ch

Fig. 1 The $\bar{B}^0 \rightarrow p \bar{p} \pi^0(\rho^0)$ decay processes, depicted as (a,b,c) for the $\bar{B}^0 \rightarrow \pi^0(\rho^0)$ transition with $0 \rightarrow p \bar{p}$ production, and (d,e,f) for the $\bar{B}^0 \rightarrow p \bar{p}$ transition with recoiled $\pi^0(\rho^0)$ meson

2 Formalism

For the tree-level dominated B meson decays, the relevant effective Hamiltonian is given by [23]

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[V_{ub} V_{ud}^* \left(\sum_{i=1,2} c_i O_i \right) - V_{tb} V_{td}^* \left(\sum_{j=3}^{10} c_j O_j \right) \right] + h.c., \quad (2)$$

where G_F is the Fermi constant, $c_{i(j)}$ the Wilson coefficients, and V_{ij} the CKM matrix elements. The four-quark operators $O_{i(j)}$ for the tree (penguin)-level contributions are written as

$$\begin{aligned} O_1 &= (\bar{d}_\alpha u_\alpha)_{V-A} (\bar{u}_\beta b_\beta)_{V-A}, \\ O_2 &= (\bar{d}_\alpha u_\beta)_{V-A} (\bar{u}_\beta b_\alpha)_{V-A}, \\ O_{3(5)} &= (\bar{d}_\alpha b_\alpha)_{V-A} \sum_q (\bar{q}_\beta q_\beta)_{V\mp A}, \\ O_{4(6)} &= (\bar{d}_\alpha b_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V\mp A}, \\ O_{7(9)} &= \frac{3}{2} (\bar{d}_\alpha b_\alpha)_{V-A} \sum_q e_q (\bar{q}_\beta q_\beta)_{V\pm A}, \\ O_{8(10)} &= \frac{3}{2} (\bar{d}_\alpha b_\beta)_{V-A} \sum_q e_q (\bar{q}_\beta q_\alpha)_{V\pm A}, \end{aligned} \quad (3)$$

where $q = (u, d, s)$, $(\bar{q}_1 q_2)_{V\pm A} = \bar{q}_1 \gamma_\mu (1 \pm \gamma_5) q_2$, and the subscripts (α, β) denote the color indices. With the identity of $\delta_{\beta\beta'} \delta_{\alpha\alpha'} = \delta_{\alpha\beta} \delta_{\alpha'\beta'} / N_c + 2 T_{\alpha\beta}^a T_{\alpha'\beta'}^a$, where $N_c = 3$ is the color number, O_i and O_{i+1} can be related. For example,

Fig. 2 The tree-level $b \rightarrow u \bar{u} d$ weak transition, where the blue blob represents the short-distance internal W -boson emission

we have $O_1 = O_2 / N_c + 2 \bar{d} \gamma_\mu (1 - \gamma_5) T^a u \bar{u} \gamma^\mu (1 - \gamma_5) T^a b$ with T^a the Gell-Mann matrices.

In the factorization ansatz [24,25], one is able to express $\langle h_1 h_2 | O | B \rangle$ as a product of two factors, $\langle h_1 | J_1 | 0 \rangle$ and $\langle h_2 | J_2 | B \rangle$, where $O = J_1 \cdot J_2$ is the product of the two color singlet quark currents J_1 and J_2 and $h_{1,2}$ denote the hadron states. The matrix elements $\langle h_1 | J_1 | 0 \rangle$ and $\langle h_2 | J_2 | B \rangle$ are obtained in such a way that the flavor quantum numbers of $J_{1,2}$ match the hadron states in the separate matrix elements. We hence decompose $\langle p \bar{p} \pi^0 | O_2 | \bar{B}^0 \rangle$ as [15,16]

$$\begin{aligned} \langle O_2 \rangle_a &= \langle \pi^0 | (\bar{u}_\beta u_\beta)_{V-A} | 0 \rangle \langle p \bar{p} | (\bar{d}_\alpha b_\alpha)_{V-A} | \bar{B}^0 \rangle, \\ \langle O_2 \rangle_d &= \langle p \bar{p} | (\bar{u}_\beta u_\beta)_{V-A} | 0 \rangle \langle \pi^0 | (\bar{d}_\alpha b_\alpha)_{V-A} | \bar{B}^0 \rangle, \end{aligned} \quad (4)$$

where the Fierz reordering has been used to exchange $(\bar{d}_\alpha, \bar{u}_\beta)$. The amplitudes $\langle O_2 \rangle_{a,d}$ correspond to the two configurations depicted in Fig. 1a, d, respectively. As depicted in Fig. 2 for the $b \rightarrow u \bar{u} d$ transition, dynamically, the d -quark moves collinearly with the spectator quark $\bar{d}$ from $\bar{B}^0(b\bar{d})$, so that in Fig. 1d the $d\bar{d}$ for the $p\bar{p}$ formation can

be seen as a consequence of the B meson transition, which is in accordance with the matrix element of $\langle p\bar{p}|(\bar{d}b)|\bar{B}^0\rangle$. Moreover, since $u\bar{u}$ and $d\bar{d}$ in the $\bar{B}^0$ rest frame can be seen to move in opposite directions, we take $\pi^0(u\bar{u})$ in Fig. 1d as the recoiled state, in accordance with $\langle\pi^0|(\bar{u}u)|0\rangle$ with $|0\rangle$ representing the vacuum. On the other hand, $\langle p\bar{p}\pi^0|O_1|\bar{B}^0\rangle$ is expressed as $\langle O_1\rangle_{a(d)} = \langle O_2\rangle_{a(d)}/N_c + \langle\chi_1\rangle$ with $\langle\chi_1\rangle \equiv \langle p\bar{p}\pi^0|2\bar{u}\gamma_\mu(1-\gamma_5)T^a d\bar{u}\gamma^\mu(1-\gamma_5)T^a b|\bar{B}^0\rangle$. The T^a in $\langle\chi_1\rangle$ correspond to the gluon exchange between the two currents, which causes an inseparable connection between the final states. Hence, $\langle\chi_1\rangle$ is regarded as the non-factorizable QCD corrections. Subsequently, we note that $\langle p\bar{p}\pi^0|c_1 O_1 + c_2 O_2|\bar{B}^0\rangle = a_2\langle O_2\rangle_{a,d}$ with $a_2 = c_2^{eff} + c_1^{eff}/N_c$, where c_i^{eff} represents the effective Wilson coefficient for c_i to receive the next-to-leading-order contributions [25]. In the generalized edition of the factorization, one varies N_c between 2 and infinity in order to estimate $\langle\chi_1\rangle$ [15, 24, 25]. This makes N_c a phenomenological parameter determined by data.

To complete the amplitudes, we extend our calculation for $\langle p\bar{p}\pi^0|c_1 O_1 + c_2 O_2|\bar{B}^0\rangle$ to the penguin-level diagrams, as depicted in Fig. 1b, c, e, f. Moreover, with π^0 replaced by ρ^0 and $\pi^+\pi^-$, we get the amplitudes of $\bar{B}^0 \rightarrow p\bar{p}\rho^0$ and $\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-$, respectively. Hence, the decay amplitudes of $\bar{B}^0 \rightarrow p\bar{p}X_M$ with $X_M \equiv (\pi^0(\rho^0), \pi^+\pi^-)$ can be written as [16, 17, 20]

$$\mathcal{A}(\bar{B}^0 \rightarrow p\bar{p}X_M) = \mathcal{A}_1(X_M) + \mathcal{A}_2(X_M), \quad (5)$$

with $\mathcal{A}_{1,2}(X_M)$ corresponding to Fig. 1a–c and d–f, respectively. Explicitly, $\mathcal{A}_{1,2}$ are given by [15–17, 25–27]

$$\begin{aligned} \mathcal{A}_1(X_M) &= \frac{G_F}{\sqrt{2}} \left\{ \left[\langle p\bar{p}|\bar{u}\gamma^\mu(\alpha_2^+ - \alpha_2^- \gamma_5)u|0\rangle \right. \right. \\ &\quad \left. \left. + \langle p\bar{p}|\bar{d}\gamma^\mu(\alpha_3^+ - \alpha_3^- \gamma_5)d|0\rangle \right] \right. \\ &\quad \times \langle X_M|\bar{d}\gamma_\mu(1-\gamma_5)b|\bar{B}^0\rangle \\ &\quad \left. + \alpha_6 \langle p\bar{p}|\bar{d}(1+\gamma_5)d|0\rangle \langle X_M|\bar{d}(1-\gamma_5)b|\bar{B}^0\rangle \right\}, \\ \mathcal{A}_2(X_M) &= \frac{G_F}{\sqrt{2}} \left\{ \left[\langle X_M|\bar{u}\gamma^\mu(\alpha_2^+ - \alpha_2^- \gamma_5)u|0\rangle \right. \right. \\ &\quad \left. \left. + \langle X_M|\bar{d}\gamma^\mu(\alpha_3^+ - \alpha_3^- \gamma_5)d|0\rangle \right] \right. \\ &\quad \times \langle p\bar{p}|\bar{d}\gamma_\mu(1-\gamma_5)b|\bar{B}^0\rangle \\ &\quad \left. + \alpha_6 \langle X_M|\bar{d}(1+\gamma_5)d|0\rangle \langle p\bar{p}|\bar{d}(1-\gamma_5)b|\bar{B}^0\rangle \right\}. \end{aligned} \quad (6)$$

The parameters α_i are defined as

$$\begin{aligned} \alpha_2^\pm &= V_{ub}V_{ud}^*a_2 - V_{tb}V_{td}^*(a_3 \pm a_5 \pm a_7 + a_9), \\ \alpha_3^\pm &= -V_{tb}V_{td}^*\left(a_3 + a_4 \pm a_5 \mp \frac{a_7}{2} - \frac{a_9}{2} - \frac{a_{10}}{2}\right), \\ \alpha_6 &= V_{tb}V_{td}^*(2a_6 - a_8), \end{aligned} \quad (7)$$

with $a_i \equiv c_i^{eff} + c_{i\pm 1}^{eff}/N_c$ for $i = \text{odd (even)}$ [25]. We note that $\mathcal{A}_2(\pi^+\pi^-)$ is neglected since $\mathcal{A}_1(\pi^+\pi^-) \gg \mathcal{A}_2(\pi^+\pi^-)$ [20].

The $B \rightarrow X_M$ transition matrix elements in $\mathcal{A}_1(X_M)$ are written as [28–31]

$$\begin{aligned} &\langle M(p)|\bar{q}\gamma_\mu b|B(p_B)\rangle \\ &= \left[(p_B + p)^\mu - \frac{m_B^2 - m_M^2}{q^2} q^\mu \right] F_1^{BM} \\ &\quad + \frac{m_B^2 - m_M^2}{q^2} q^\mu F_0^{BM}, \\ &\langle M^*(p)|\bar{q}\gamma_\mu b|B(p_B)\rangle = \epsilon_{\mu\nu\alpha\beta} \epsilon^{*\nu} p_B^\alpha p^\beta \frac{2V_1}{m_B + m_{M^*}}, \\ &\langle M^*(p)|q\gamma_\mu \gamma_5 b|B(p_B)\rangle \\ &= i \left[\epsilon_\mu^* - \frac{\epsilon^* \cdot q}{q^2} q_\mu \right] (m_B + m_{M^*}) A_1 \\ &\quad + i \frac{\epsilon^* \cdot q}{q^2} q_\mu (2m_{M^*}) A_0 \\ &\quad - i \left[(p_B + p)_\mu - \frac{m_B^2 - m_{M^*}^2}{q^2} q_\mu \right] (\epsilon^* \cdot q) \frac{A_2}{m_B + m_{M^*}}, \\ &\langle M_1(p_1)M_2(p_2)|\bar{q}\gamma_\mu(1-\gamma_5)b|B(p_B)\rangle \\ &= \epsilon_{\mu\nu\alpha\beta} p_B^\nu (p_2 + p_1)^\alpha (p_2 - p_1)^\beta h \\ &\quad + i w_+ (p_2 + p_1)_\mu + i w_- (p_2 - p_1)_\mu + i r q_\mu, \end{aligned} \quad (8)$$

where ϵ_μ is the polarization vector of M^* , $q_\mu = (p_B - p)_\mu = (p_B - p_1 - p_2)_\mu$ as the momentum transfer for the $B \rightarrow X_M$ transition, ($F_{0,1}^{BM}$, V_1 , $A_{0,1,2}$) the $B \rightarrow M^{(*)}$ transition form factors and (h , r , $w_\pm$) the $B \rightarrow M_1 M_2$ transition form factors.

The matrix elements of $0 \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ are expressed as [27]

$$\begin{aligned} \langle \mathbf{B}\bar{\mathbf{B}}'|\bar{q}\gamma_\mu q'|0\rangle &= \bar{u} \left[F_1 \gamma_\mu + \frac{F_2}{m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}} i \sigma_{\mu\nu} q^\nu \right] v, \\ \langle \mathbf{B}\bar{\mathbf{B}}'|\bar{q}\gamma_\mu \gamma_5 q'|0\rangle &= \bar{u} \left[g_A \gamma_\mu + \frac{h_A}{m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}} q_\mu \right] \gamma_5 v, \\ \langle \mathbf{B}\bar{\mathbf{B}}'|\bar{q}q'|0\rangle &= f_S \bar{u} v, \quad \langle \mathbf{B}\bar{\mathbf{B}}'|q\gamma_5 q'|0\rangle = g_P \bar{u} \gamma_5 v, \end{aligned} \quad (9)$$

where $u(v)$ is the (anti-)baryon spinor, and $F_{1,2}$, g_A , h_A , f_S , g_P the timelike baryonic form factors.

In $\mathcal{A}_2(\bar{B}^0 \rightarrow p\bar{p}M^{(*)0})$, the $0 \rightarrow M^{(*)}$ matrix elements are written as [1]

$$\langle M(p)|\bar{q}\gamma_\mu \gamma_5 q'|0\rangle = -i f_M p_\mu, \quad \langle M^*|\bar{q}\gamma_\mu q'|0\rangle = m_{M^*} f_{M^*} \epsilon_\mu^*, \quad (10)$$

with $f_{M^{(*)}}$ the decay constant. For the $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ transitions we have [13, 26]

$$\begin{aligned} \langle \mathbf{B}\bar{\mathbf{B}}' | \bar{q} \gamma_\mu b | B \rangle &= i\bar{u}[g_1 \gamma_\mu + g_2 i \sigma_{\mu\nu} \hat{p}^\nu + g_3 \hat{p}_\mu + g_4 (p_{\bar{\mathbf{B}}'} \\ &\quad + p_{\mathbf{B}})_\mu + g_5 (p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu] \gamma_5 v, \\ \langle \mathbf{B}\bar{\mathbf{B}}' | \bar{q} \gamma_\mu \gamma_5 b | B \rangle &= i\bar{u}[f_1 \gamma_\mu + f_2 i \sigma_{\mu\nu} \hat{p}^\nu + f_3 \hat{p}_\mu \\ &\quad + f_4 (p_{\bar{\mathbf{B}}'} + p_{\mathbf{B}})_\mu + f_5 (p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu] v, \\ \langle \mathbf{B}\bar{\mathbf{B}}' | \bar{q} b | B \rangle &= i\bar{u}[\bar{g}_1 \hat{p} + \bar{g}_2 (E_{\bar{\mathbf{B}}'} + E_{\mathbf{B}}) \\ &\quad + \bar{g}_3 (E_{\bar{\mathbf{B}}'} - E_{\mathbf{B}})] \gamma_5 v, \\ \langle \mathbf{B}\bar{\mathbf{B}}' | \bar{q} \gamma_5 b | B \rangle &= i\bar{u}[\bar{f}_1 \hat{p} + \bar{f}_2 (E_{\bar{\mathbf{B}}'} + E_{\mathbf{B}}) \\ &\quad + \bar{f}_3 (E_{\bar{\mathbf{B}}'} - E_{\mathbf{B}})] v, \end{aligned} \quad (11)$$

where $\hat{p}_\mu = (p_B - p_{\mathbf{B}} - p_{\bar{\mathbf{B}}'})_\mu$, $g_i(f_i)$ ($i = 1, 2, \dots, 5$) and $\bar{g}_j(\bar{f}_j)$ ($j = 1, 2, 3$) are the $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ transition form factors.

The mesonic and baryonic form factors have momentum dependencies. For $B \rightarrow M^{(*)}$, they are given by [32]

$$\begin{aligned} F_A(q^2) &= \frac{F_A(0)}{\left(1 - \frac{q^2}{M_A^2}\right) \left(1 - \frac{\sigma_1 q^2}{M_A^2} + \frac{\sigma_2 q^4}{M_A^4}\right)}, \\ F_B(q^2) &= \frac{F_B(0)}{1 - \frac{\sigma_1 q^2}{M_B^2} + \frac{\sigma_2 q^4}{M_B^4}}, \end{aligned} \quad (12)$$

where $F_A = (F_1^{BM}, V_1, A_0)$ and $F_B = (F_0^{BM}, A_{1,2})$. According to the approach of perturbative QCD counting rules, one presents the momentum dependencies of the form factors for $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$, $0 \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ and $B \rightarrow M_1 M_2$ as [13, 26, 33–37]

$$\begin{aligned} F_1 &= \frac{\bar{C}_{F_1}}{t^2}, \quad g_A = \frac{\bar{C}_{g_A}}{t^2}, \quad f_s = \frac{\bar{C}_{f_s}}{t^2}, \quad g_P = \frac{\bar{C}_{g_P}}{t^2}, \\ f_i &= \frac{D_{f_i}}{t^3}, \quad g_i = \frac{D_{g_i}}{t^3}, \quad \bar{f}_i = \frac{D_{\bar{f}_i}}{t^3}, \quad \bar{g}_i = \frac{D_{\bar{g}_i}}{t^3}, \\ h &= \frac{C_h}{s^2}, \quad w_- = \frac{D_{w_-}}{s^2}, \end{aligned} \quad (13)$$

where $t \equiv (p_{\mathbf{B}} + p_{\bar{\mathbf{B}}'})^2$, $s \equiv (p_1 + p_2)^2$, and $\bar{C}_i = C_i [\ln(t/\Lambda_0^2)]^{-\gamma}$ with $\gamma = 2.148$ and $\Lambda_0 = 0.3$ GeV. In Ref. [38], $F_2 = F_1/(t \ln[t/\Lambda_0^2])$ is calculated to be much less than F_1 ; hence we neglect it. Since h_A corresponds to the smallness of $\mathcal{B}(\bar{B}^0 \rightarrow p \bar{p}) \sim 10^{-8}$ [39–41], we neglect h_A as well. The terms (r, w_+) in Eq. (8) are neglected – following Refs. [36, 37] – due to the fact that their parity quantum numbers disagree with the experimental evidence of $J^P = 1^-$ for the meson-pair production [42].

The constants C_i (D_i) can be decomposed into sets of parameters that obey the $SU(3)$ flavor and $SU(2)$ spin symmetries. In Refs. [13, 15, 17, 20, 26, 27, 33, 34, 43, 44], they are derived as

Table 1 The $\bar{B}^0 \rightarrow M^{(*)0}$ transition form factors at zero-momentum transfer, with $(M_A, M_B) = (5.32, 5.32)$ and $(5.27, 5.32)$ GeV for π and ρ , respectively

$\bar{B}^0 \rightarrow \pi^0, \rho^0$	$F_1^{B\pi}$	$F_0^{B\pi}$	V_1	A_0	A_1	A_2
$\sqrt{2}f(0)$	0.29	0.29	0.31	0.30	0.26	0.24
σ_1	0.48	0.76	0.59	0.54	0.73	1.40
σ_2	–	0.28	–	–	0.10	0.50

$$\begin{aligned} (C_{F_1}, C_{g_A}) &= \frac{1}{3}(5C_{||} + C_{||}, 5C_{||}^* - C_{||}^*), \quad (\text{for } \langle p \bar{p} | (\bar{u}u)_{V,A} | 0 \rangle) \\ (C_{F_1}, C_{g_A}, C_{f_s}, C_{g_P}) &= \frac{1}{3}(C_{||} + 2C_{||}, C_{||}^* - 2C_{||}^*, \bar{C}_{||}, \bar{C}_{||}^*), \\ (\text{for } \langle p \bar{p} | (\bar{d}d)_{V,A,S,P} | 0 \rangle) & \\ (D_{g_1, f_1}, D_{g_j}, D_{f_j}) &= \frac{1}{3}(D_{||} \mp 2D_{||}, -D_{||}^j, D_{||}^j), \\ (\text{for } \langle p \bar{p} | (\bar{d}d)_{V,A} | \bar{B}^0 \rangle) & \\ (D_{\bar{g}_1, \bar{f}_1}, D_{\bar{g}_{2,3}}, D_{\bar{f}_{2,3}}) &= \frac{1}{3}(\bar{D}_{||} \mp 2\bar{D}_{||}, -\bar{D}_{||}^{2,3}, -\bar{D}_{||}^{2,3}), \\ (\text{for } \langle p \bar{p} | (\bar{d}d)_{S,P} | \bar{B}^0 \rangle) & \end{aligned} \quad (14)$$

with $j = 2, \dots, 4, 5$, $C_{||(\bar{||})}^* \equiv C_{||(\bar{||})} + \delta C_{||(\bar{||})}$ and $\bar{C}_{||}^* \equiv \bar{C}_{||} + \delta \bar{C}_{||}$. The direct CP violating asymmetry is defined as

$$\begin{aligned} \mathcal{A}_{CP}(B \rightarrow \mathbf{B}\bar{\mathbf{B}}' X_M) &= \frac{\Gamma(B \rightarrow \mathbf{B}\bar{\mathbf{B}}' X_M) - \Gamma(\bar{B} \rightarrow \bar{\mathbf{B}}\bar{\mathbf{B}}' \bar{X}_M)}{\Gamma(B \rightarrow \mathbf{B}\bar{\mathbf{B}}' X_M) + \Gamma(\bar{B} \rightarrow \bar{\mathbf{B}}\bar{\mathbf{B}}' \bar{X}_M)}, \end{aligned} \quad (15)$$

where $\bar{B} \rightarrow \bar{\mathbf{B}}\bar{\mathbf{B}}' \bar{X}_M$ denotes the anti-particle decay.

3 Numerical analysis

We use the following values for the numerical analysis. The CKM matrix elements are calculated via the Wolfenstein parameterization [1], with the world-average values

$$\begin{aligned} \lambda &= 0.22453 \pm 0.00044, \quad A = 0.836 \pm 0.015, \\ \bar{\rho} &= 0.122_{-0.017}^{+0.018}, \quad \bar{\eta} = 0.355_{-0.011}^{+0.012}. \end{aligned} \quad (16)$$

The decay constants are $f_{\pi, \rho} = (130.4 \pm 0.2, 210.6 \pm 0.4)$ MeV [1], with $(f_{\pi^0}, f_{\rho^0}) = (f_\pi, f_\rho)/\sqrt{2}$. We adopt the $B \rightarrow M^{(*)}$ transition form factors in Ref. [32], listed in Table 1. In Sect. 2, N_c has been presented as the phenomenological parameter determined by data. Empirically, one is able to determine N_c between 2 and ∞ . With the nearly universal value for N_c in the specific decays, the

Table 2 Decay branching fractions and direct CP asymmetries of $\bar{B}^0 \rightarrow p\bar{p}X_M$, where the first errors come from the estimations of the non-factorizable effects, the second ones from the uncertainties of the CKM matrix elements, and the third ones from those of the decay constants and form factors

	Our result	Data
$10^7 \mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0)$	$5.0 \pm 1.9 \pm 0.3 \pm 0.9$	5.0 ± 1.9 [22]
$10^7 \mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\rho^0)$	$1.8 \pm 1.1 \pm 0.1 \pm 0.4$	–
$10^6 \mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-)$	$2.7 \pm 0.2 \pm 0.2 \pm 0.7$	2.7 ± 0.2 [19]
$\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\pi^0)$	$(-16.8 \pm 4.8 \pm 1.6 \pm 1.8)\%$	–
$\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\rho^0)$	$(-12.6 \pm 2.2 \pm 1.2 \pm 1.7)\%$	–
$\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-)$	$(-11.4 \pm 0.2 \pm 1.2 \pm 1.4)\%$	–

factorization is demonstrated to be valid. For the tree-level internal W -emission dominated b -hadron decays, the extraction has given $N_c \simeq 2$ that corresponds to $a_2 \sim \mathcal{O}(0.2 - 0.3)$ [15, 20, 45–49], where δN_c differs due to the experimental uncertainties. For example, one obtains $N_c = 2.15 \pm 0.17$ in $\Lambda_b \rightarrow \mathbf{B}M_c$ [47, 48]. Here, we test if $N_c \simeq 2$ can be used to explain the measured $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0, p\bar{p}\pi^+\pi^-)$.

The C_{h,w_-} for $\bar{B}^0 \rightarrow \pi^+\pi^-$ and $C_i(D_i)$ for $0 \rightarrow p\bar{p}$ ($\bar{B}^0 \rightarrow p\bar{p}$) have been determined to be [15, 17, 20]

$$\begin{aligned}
 (C_h, C_{w_-}) &= (3.6 \pm 0.3, 0.7 \pm 0.2) \text{ GeV}^3, \\
 (C_{||}, C_{\perp}, \bar{C}_{||}) &= (154.4 \pm 12.1, 18.1 \\
 &\quad \pm 72.2, 537.6 \pm 28.7) \text{ GeV}^4, \\
 (\delta C_{||}, \delta C_{\perp}, \delta \bar{C}_{||}) &= (19.3 \pm 21.6, -477.4 \pm 99.0, -342.3 \pm 61.4) \text{ GeV}^4, \\
 (D_{||}, D_{\perp}) &= (45.7 \pm 33.8, -298.2 \pm 34.0) \text{ GeV}^5, \\
 (D_{||}^2, D_{||}^3, D_{||}^4, D_{||}^5) &= (33.1 \pm 30.7, -203.6 \pm 133.4, 6.5 \\
 &\quad \pm 18.1, -147.1 \pm 29.3) \text{ GeV}^4, \\
 (\bar{D}_{||}, \bar{D}_{\perp}, \bar{D}_{||}^2, \bar{D}_{||}^3) &= (35.2 \pm 4.8, -38.2 \pm 7.5, -22.3 \pm 10.2, 504.5 \\
 &\quad \pm 32.4) \text{ GeV}^4.
 \end{aligned} \tag{17}$$

For α_i in Eq. (7), the effective Wilson coefficients c_i^{eff} are calculated at the m_b scale in the NDR scheme, see Ref. [25]. They are related to the size of the decay, where the strong phases, together with the weak phase in V_{ub} and V_{td} , play the key role in $\mathcal{A}_{CP}$.

Our results for the branching fractions and CP violating asymmetries of $\bar{B}^0 \rightarrow p\bar{p}X_M$ decays are summarized in Table 2, where we have averaged the particle and antiparticle contributions for the total branching fractions.

4 Discussions and conclusions

The improved theoretical approaches such as QCD factorization (QCDF) and soft-collinear effective theory have been applied to two-body mesonic B decays [50–52]. Hence, the non-factorizable corrections of order $1/N_c^n$ with $n = 1, 2$ have been considered by calculating the vertex correc-

tions from the hard gluon exchange and the hard spectator scattering. Unfortunately, there exist no similar approaches well applied to the $B \rightarrow M_1 M_2 M_3$, $\mathbf{B}\bar{\mathbf{B}}'M$ and $\mathbf{B}\bar{\mathbf{B}}'MM'$ decays, due to the wave functions of $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'(MM')$ not as clear as those of $B \rightarrow M$. By varying N_c from 2 to ∞ , one can still estimate the non-factorizable QCD effects with the corrections of order $1/N_c$. This relies on the generalized factorization, demonstrated to work well in $B \rightarrow M_1 M_2 M_3$, $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$, $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'M(\mathbf{B}\bar{\mathbf{B}}'MM')$, $B \rightarrow D\pi$ and $\Lambda_b \rightarrow \mathbf{B}M(\Lambda_c^+\pi^-)$ [26, 36, 37, 39, 53–57]. We determine $N_c = (2.15 \pm 0.20, 1.90 \pm 0.03)$ to interpret $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0, p\bar{p}\pi^+\pi^-)$ with δN_c receiving the experimental uncertainties, which are indeed close to $N_c \simeq 2$ used in $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'M$ and $\Lambda_b \rightarrow \mathbf{B}M_{(c)}$ [15, 47–49].

In Table 2, $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0) = 5.0 \times 10^{-7}$ receives the contributions from $\mathcal{A}_1, \mathcal{A}_2$ and their interference, denoted by $\mathcal{A}_{1 \times 2}$, which give $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0) = \mathcal{B}_1 + \mathcal{B}_2 + \mathcal{B}_{1 \times 2}$ with $(\mathcal{B}_1, \mathcal{B}_2, \mathcal{B}_{1 \times 2}) = (3.82, 0.33, 0.85) \times 10^{-7}$. The $\mathcal{B}_{1 \times 2} > 0$ indicates constructive interference between $\mathcal{A}_{1,2}$. By adopting N_c from $\bar{B}^0 \rightarrow p\bar{p}\pi^0$, we predict $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\rho^0)$. We find $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\rho^0) \approx \mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0)/3$ with $(\mathcal{B}_1, \mathcal{B}_2, \mathcal{B}_{1 \times 2}) = (2.00, 0.04, -0.24) \times 10^{-7}$. The minus sign of $\mathcal{B}_{1 \times 2}$ indicates destructive interference.

With the theoretical approach reasonably well established for the branching fractions, one can have reliable predictions for CP violation. For example, $\mathcal{A}_{CP}(B^- \rightarrow p\bar{p}M^{(*)-})$ with $M^{(*)-} = (K^{*-}, K^-, \pi^-)$ were predicted as $(22 \pm 4, 6 \pm 1, -6 \pm 1)\%$ [43, 44], agreeing with the experimental values of $(21 \pm 16, 2.1 \pm 2.0 \pm 0.4, -4.1 \pm 3.9 \pm 0.5)\%$ [1, 5]. Here, our predictions for $\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\pi^0(\rho^0), p\bar{p}\pi^+\pi^-)$ are around $-(10 - 20)\%$. With $\delta \mathcal{A}_{CP}$ denoting the uncertainty for $\mathcal{A}_{CP}$, we present $\delta \mathcal{A}_{CP} \simeq (0.2 - 0.3)\mathcal{A}_{CP}$, which receives the theoretical uncertainties from the non-factorizable strong interaction, CKM matrix elements, form factors and decay constants.

Expressing the decay amplitude as $\mathcal{A} = T e^{i\delta_W} + P e^{i\delta_S}$, the CP asymmetry can be derived as

$$\mathcal{A}_{CP} = \frac{2R \sin \delta_W \sin \delta_S}{1 + 2R \cos \delta_W \cos \delta_S + R^2}, \tag{18}$$

where δ_W and δ_S are the weak and strong phases arising from the tree (T) and penguin (P)-level contributions, and

the ratio $R \equiv P/T$ suggests that a more suppressed T amplitude is able to cause a more sizeable $\mathcal{A}_{CP}$. Although $\bar{B}^0 \rightarrow p\bar{p}X_M$ involves complicated amplitudes, the relation in Eq. (18) can be used as a simple description for $\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}X_M)$. Being external and internal W -emission decays, $B^- \rightarrow p\bar{p}\pi^-$ and $\bar{B}^0 \rightarrow p\bar{p}\pi^0$ proceed with $a_1 \sim \mathcal{O}(1.0)$ and $a_2 \sim \mathcal{O}(0.2 - 0.3)$ in the tree-level amplitudes [43,44], respectively. Consequently, the more suppressed T amplitude with a_2 causes more interfering effect with the penguin diagrams, which corresponds to $|\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\pi^0)| > |\mathcal{A}_{CP}(B^- \rightarrow p\bar{p}\pi^-)|$. In fact, we predict $|\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\pi^0)| = (16.8 \pm 5.4)\%$, which is three times larger than $|\mathcal{A}_{CP}(B^- \rightarrow p\bar{p}\pi^-)|$ [43,44]. For the same reason, $|\mathcal{A}_{CP}(\bar{B}^0 \rightarrow p\bar{p}\rho^0, p\bar{p}\pi^+\pi^-)|$ can be as large as $(10 - 20)\%$.

Since $\mathcal{B}(\bar{B}^0 \rightarrow p\bar{p}\pi^0, p\bar{p}\pi^+\pi^-)$ are measured as large as 10^{-6} , and well explained by the theory, with the predicted $|\mathcal{A}_{CP}| > 10\%$, they become promising decays for measuring CP violation. By contrast, $\bar{B}^0 \rightarrow p\bar{p}\rho^0$ as well as the internal W -emission dominated Λ_b decays of $\Lambda_b^0 \rightarrow n\pi^0, n\rho^0$ have $\mathcal{B} \simeq (1 - 2) \times 10^{-7}$, which make CP measurements a challenge even in the case of large $|\mathcal{A}_{CP}| > 10\%$ [49].

In summary, we have investigated the branching fractions and direct CP violating asymmetries of the $\bar{B}^0 \rightarrow p\bar{p}\pi^0(\rho^0)$ and $\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-$ decays. We have shown that these baryonic B -meson decays mediated dominantly through internal W -emission processes are promising processes to observe for the first time the CP violating effects in B decays to final states with half-spin particles.

With a large predicted CP asymmetry $\mathcal{A}_{CP} = (-16.8 \pm 5.4)\%$, which is accessible to the Belle II experiment, $\bar{B}^0 \rightarrow p\bar{p}\pi^0$ is particularly suited for a potential first observation of CP violation in baryonic B decays in the coming years. Furthermore, the $\bar{B}^0 \rightarrow p\bar{p}\pi^+\pi^-$ decay, with its branching fraction of order 10^{-6} and the large predicted direct CP asymmetry $\mathcal{A}_{CP} \sim -(10 - 20)\%$, is also in the realm of both Belle II and LHCb experiments.

Acknowledgements This work was supported in part by National Science Foundation of China (11675030) and U. S. National Science Foundation award ACI-1450319.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: The data used in this paper are publicly available and they can be found in the corresponding references.]

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended

use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.
Funded by SCOAP³.

References

1. M. Tanabashi et al., [Particle Data Group], Phys. Rev. D **98**, 030001 (2018)
2. R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. **122**, 211803 (2019)
3. Please consult with the review: "CP Violation in the Quark Sector" in [1]
4. R. Aaij et al., [LHCb Collaboration], Nature Phys. **13**, 391–396 (2017)
5. R. Aaij et al., [LHCb Collaboration], Phys. Rev. Lett. **113**, 141801 (2014)
6. K. Abe et al., [Belle Collaboration], Phys. Rev. Lett. **88**, 181803 (2002)
7. B. Aubert et al., [BaBar Collaboration], Phys. Rev. D **72**, 051101 (2005)
8. B. Aubert et al., [BaBar Collaboration], Phys. Rev. D **74**, 051101 (2006)
9. J.T. Wei et al., [Belle Collaboration], Phys. Lett. B **659**, 80 (2008)
10. J.H. Chen et al., [Belle Collaboration], Phys. Rev. Lett. **100**, 251801 (2008)
11. R. Aaij et al., [LHCb Collaboration], Phys. Rev. D **88**, 052015 (2013)
12. W.S. Hou, A. Soni, Phys. Rev. Lett. **86**, 4247 (2001)
13. C.Q. Geng, Y.K. Hsiao, Phys. Rev. D **74**, 094023 (2006)
14. M. Suzuki, J. Phys. G **34**, 283 (2007)
15. Y.K. Hsiao, C.Q. Geng, Phys. Rev. D **93**, 034036 (2016)
16. Y.K. Hsiao, C.Q. Geng, Y. Yu, H.J. Zhao, Eur. Phys. J. C **79**, 433 (2019)
17. C.Q. Geng, Y.K. Hsiao, E. Rodrigues, Phys. Lett. B **767**, 205 (2017)
18. R. Aaij et al., [LHCb Collaboration], Phys. Rev. Lett. **119**, 041802 (2017)
19. R. Aaij et al., [LHCb Collaboration], Phys. Rev. D **96**, 051103 (2017)
20. Y.K. Hsiao, C.Q. Geng, Phys. Lett. B **770**, 348 (2017)
21. P.C. Lu et al., [Belle Collaboration], Phys. Rev. D **99**, 032003 (2019)
22. B. Pal et al., [Belle Collaboration], Phys. Rev. D **99**, 091104 (2019)
23. A.J. Buras, [arXiv:hep-ph/9806471](https://arxiv.org/abs/hep-ph/9806471)
24. M. Bauer, B. Stech, M. Wirbel, Z. Phys. C **34**, 103 (1987)
25. A. Ali, G. Kramer, C.D. Lu, Phys. Rev. D **58**, 094009 (1998)
26. C.K. Chua, W.S. Hou, S.Y. Tsai, Phys. Rev. D **66**, 054004 (2002)
27. C.K. Chua, W.S. Hou, Eur. Phys. J. C **29**, 27 (2003)
28. M. Wirbel, B. Stech, M. Bauer, Z. Phys. C **29**, 637 (1985)
29. M. Wirbel, B. Stech, M. Bauer, Z. Phys. C **34**, 103 (1987)
30. M. Bauer, M. Wirbel, Z. Phys. C **42**, 671 (1989)
31. C.L.Y. Lee, M. Lu, M.B. Wise, Phys. Rev. D **46**, 5040 (1992)
32. D. Melikhov, B. Stech, Phys. Rev. D **62**, 014006 (2000)
33. S.J. Brodsky, G.R. Farrar, Phys. Rev. Lett. **31**, 1153 (1973)
34. S.J. Brodsky, G.R. Farrar, Phys. Rev. D **11**, 1309 (1975)
35. S.J. Brodsky, C.E. Carlson, J.R. Hiller, D.S. Hwang, Phys. Rev. D **69**, 054022 (2004)
36. C.K. Chua, W.S. Hou, S.Y. Shiao, S.Y. Tsai, Phys. Rev. D **67**, 034012 (2003)
37. C.K. Chua, W.S. Hou, S.Y. Shiao, S.Y. Tsai, Eur. Phys. J. C **33**, S253 (2004)
38. A.V. Belitsky, X.D. Ji, F. Yuan, Phys. Rev. Lett. **91**, 092003 (2003)
39. Y.K. Hsiao, C.Q. Geng, Phys. Rev. D **91**, 077501 (2015)

40. R. Aaij et al., [LHCb Collaboration], JHEP **10**, 005 (2013)
41. R. Aaij et al., [LHCb Collaboration], Phys. Rev. Lett. **119**, 232001 (2017)
42. A. Drutskoy et al., [Belle Collaboration], Phys. Lett. B **542**, 171 (2002)
43. C.Q. Geng, Y.K. Hsiao, J.N. Ng, Phys. Rev. Lett. **98**, 011801 (2007)
44. C.Q. Geng, Y.K. Hsiao, Int. J. Mod. Phys. A **23**, 3290 (2008)
45. A.J. Buras, Nucl. Phys. B **434**, 606 (1995)
46. M. Neubert, A.A. Petrov, Phys. Lett. B **519**, 50 (2001)
47. Y.K. Hsiao, P.Y. Lin, L.W. Luo, C.Q. Geng, Phys. Lett. B **751**, 127 (2015)
48. Y.K. Hsiao, P.Y. Lin, C.C. Lih, C.Q. Geng, Phys. Rev. D **92**, 114013 (2015)
49. Y.K. Hsiao, Y. Yao, C.Q. Geng, Phys. Rev. D **95**, 093001 (2017)
50. M. Beneke, G. Buchalla, M. Neubert, C.T. Sachrajda, Nucl. Phys. B **591**, 313 (2000)
51. M. Beneke, G. Buchalla, M. Neubert, C.T. Sachrajda, Nucl. Phys. B **606**, 245 (2001)
52. C.W. Bauer, D. Pirjol, I.W. Stewart, Phys. Rev. D **65**, 054022 (2002)
53. H.Y. Cheng, C.K. Chua, Z.Q. Zhang, Phys. Rev. D **94**, 094015 (2016)
54. H.Y. Cheng, C.K. Chua, A. Soni, Phys. Rev. D **72**, 094003 (2005)
55. Y.K. Hsiao, C.Q. Geng, Phys. Rev. D **91**, 116007 (2015)
56. C.W. Bauer, D. Pirjol, I.W. Stewart, Phys. Rev. Lett. **87**, 201806 (2001)
57. A.K. Leibovich, Z. Ligeti, I.W. Stewart, M.B. Wise, Phys. Lett. B **586**, 337 (2004)