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Review Article

Baryonic B Meson Decays

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We review the two- and three-body baryonic B decays with the dibaryon ($\mathbf{B}\overline{\mathbf{B}'}$) as the final states. Accordingly, we summarize the experimental data of the branching fractions, angular asymmetries, and CP asymmetries. Using the W-boson annihilation (exchange) mechanism, the branching fractions of $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$ are shown to be interpretable. In the approach of perturbative QCD counting rules, we study the three-body decay channels. In particular, we review the CP asymmetries of $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M$, which are promising to be measured by the LHCb and Belle II experiments. Finally, we remark the theoretical challenges in interpreting $\mathscr{B}(B^- \longrightarrow p\bar{p}\rho^-)$ and $\mathscr{B}(B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu)$.

1. Introduction

The baryonic B meson decays have been richly measured with the branching fractions, angular asymmetries, and CP asymmetries in two- and three-body decay channels [1–13], as summarized in Table 1. Typically, $\mathscr{B}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'})$ is as small as $10^{-8} - 10^{-7}$. Nonetheless, it is observed that $\mathscr{B}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M) \sim (10-100) \times \mathscr{B}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'})$, due to a sharply rising peak in $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M$ observed around the threshold area of $m_{\mathbf{B}\overline{\mathbf{B}'}} \sim m_\mathbf{B} + m_{\overline{\mathbf{B}'}}$ in the dibaryon invariant mass spectrum [4]. Known as the threshold effect, it enhances $\mathscr{B}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M)$ as large as 10^{-6}. While the $\mathbf{B}\overline{\mathbf{B}'}$ production shows the tendency to occur around $m_{\mathbf{B}\overline{\mathbf{B}'}} \sim m_\mathbf{B} + m_{\mathbf{B}'}$, $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$ proceeds at m_B scale, far from the threshold area. This interprets the suppressed $\mathscr{B}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'})$ [14, 15].

The partial branching fraction of $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M$ can be a function of $\cos\theta_\mathbf{B}$, where $\theta_\mathbf{B}$ is the angle between the baryon and meson moving directions in the dibaryon rest frame. One hence defines the forward-backward angular asymmetry,

$$\mathscr{A}_{\mathrm{FB}} \equiv \frac{\mathscr{B}(\cos\theta_\mathbf{B} > 0) - B(\cos\theta_\mathbf{B} < 0)}{\mathscr{B}(\cos\theta_\mathbf{B} > 0) + B(\cos\theta_\mathbf{B} < 0)}. \tag{1}$$

In Table 1, $\mathscr{A}_{\mathrm{FB}}(B^- \longrightarrow p\bar{p}\pi^-, p\bar{p}K^-) = (-40.9 \pm 3.4, 49.5 \pm 1.4)\%$ [2] indicate that one of the dibaryons favors to move collinearly with the meson.

We search for the theoretical approach to interpret the threshold effect, branching fractions, and angular asymmetries of the baryonic B decays. We find that the factorization approach can be useful [16], where one factorizes (decomposes) the amplitude of the decay as two separate matrix elements. In our case, we present

$$\begin{aligned}
\mathscr{M}\left(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}\right) &\propto \left\langle \mathbf{B}\overline{\mathbf{B}'} | \bar{q}q' | 0 \right\rangle \langle 0 | \bar{q}b | B \rangle, \\
\mathscr{M}_1\left(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M\right) &\propto \left\langle \mathbf{B}\overline{\mathbf{B}'} \middle| \left(\bar{q}q'\right) \middle| 0 \right\rangle \langle M | (\bar{q}b) | B \rangle, \\
\mathscr{M}_2\left(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M\right) &\propto \left\langle M | \bar{q}q' | 0 \right\rangle \left\langle \mathbf{B}\overline{\mathbf{B}'} | \bar{q}b | B \right\rangle,
\end{aligned} \tag{2}$$

Table 1: The measured branching fractions, forward-backward asymmetries ($\mathcal{A}_{\rm FB}$), and CP asymmetries ($\mathcal{A}_{\rm CP}$) for the baryonic B decays, where the notation † is for $\mathcal{A}_{\rm FB}$ with $m_{p\bar{p}} < 2.85$ GeV.

Decay mode	Branching fraction	$\mathcal{A}_{\rm FB}$	$\mathcal{A}_{\rm CP}$	Ref.
$\bar{B}^0 \longrightarrow p\bar{p}$	$(1.25 \pm 0.32) \times 10^{-8}$			[1]
$\bar{B}^0 \longrightarrow \Lambda\bar{\Lambda}$	$<3.2 \times 10^{-7}$			[1]
$B^- \longrightarrow \Lambda\bar{p}$	$\left(2.4^{+1.0}_{-0.9}\right) \times 10^{-7}$			[1]
$\bar{B}^0_s \longrightarrow p\bar{p}$	$<1.5 \times 10^{-8}$			[1]
$\bar{B}^0 \longrightarrow p\bar{p}\pi^0$	$(5.0 \pm 1.9) \times 10^{-7}$			[1]
$\bar{B}^0 \longrightarrow p\bar{p}\bar{K}^0$	$(2.66 \pm 0.32) \times 10^{-6}$			[1]
$\bar{B}^0 \longrightarrow \Lambda\bar{p}\pi^+$	$(3.14 \pm 0.29) \times 10^{-6}$	$-0.41 \pm 0.11 \pm 0.03$	0.04 ± 0.07	[1, 12]
$\bar{B}^0 \longrightarrow \Sigma^0\bar{p}\pi^+$	$<3.8 \times 10^{-6}$			[1]
$\bar{B}^0 \longrightarrow \Lambda\bar{p}K^+$	$<8.2 \times 10^{-7}$			[1]
$\bar{B}^0 \longrightarrow \Lambda\bar{\Lambda}\bar{K}^0$	$\left(4.8^{+1.0}_{-0.9}\right) \times 10^{-6}$			[1]
$B^- \longrightarrow p\bar{p}\pi^-$	$(1.62 \pm 0.20) \times 10^{-6}$	$(-0.409 \pm 0.033 \pm 0.006)^\dagger$	0.00 ± 0.04	[1, 2]
$B^- \longrightarrow p\bar{p}K^-$	$(5.9 \pm 0.5) \times 10^{-6}$	$(0.495 \pm 0.012 \pm 0.007)^\dagger$	0.00 ± 0.04	[1, 2]
$B^- \longrightarrow \Lambda\bar{p}\pi^0$	$\left(3.0^{+0.7}_{-0.6}\right) \times 10^{-6}$	$-0.16 \pm 0.18 \pm 0.03$	0.01 ± 0.17	[1, 12]
$B^- \longrightarrow \Lambda\bar{\Lambda}\pi^-$	$<9.4 \times 10^{-7}$			[1]
$B^- \longrightarrow \Lambda\bar{\Lambda}K^-$	$(3.4 \pm 0.6) \times 10^{-6}$			[1]
$\bar{B}^0_s \longrightarrow \bar{p}\Lambda K^+$+c.c.	$(5.5 \pm 1.0) \times 10^{-6}$			[1]
$\bar{B}^0 \longrightarrow p\bar{p}\bar{K}^{*0}$	$\left(1.24^{+0.28}_{-0.25}\right) \times 10^{-6}$		0.05 ± 0.12	[1]
$\bar{B}^0 \longrightarrow \Lambda\bar{\Lambda}\bar{K}^{*0}$	$\left(2.5^{+0.9}_{-0.8}\right) \times 10^{-6}$			[1]
$B^- \longrightarrow p\bar{p}K^{*-}$	$\left(3.6^{+0.8}_{-0.7}\right) \times 10^{-6}$		0.21 ± 0.16	[1]
$B^- \longrightarrow \Lambda\bar{p}\rho^0, \rho^0 \longrightarrow \pi^+\pi^-$	$(4.8 \pm 0.9) \times 10^{-6}$			[1]
$B^- \longrightarrow \Lambda\bar{p}\phi$	$(8.0 \pm 2.2) \times 10^{-7}$			[1]
$B^- \longrightarrow \Lambda\bar{\Lambda}K^{*-}$	$\left(2.2^{+1.2}_{-0.9}\right) \times 10^{-6}$			[1]
$\bar{B}^0 \longrightarrow \Lambda_c^+\bar{p}$	$(1.54 \pm 0.18) \times 10^{-5}$			[1]
$\bar{B}^0 \longrightarrow \Sigma_c^+\bar{p}$	$<2.4 \times 10^{-5}$			[1]
$B^- \longrightarrow \Sigma_c^0\bar{p}$	$(2.9 \pm 0.7) \times 10^{-5}$			[1]
$B^- \longrightarrow p\bar{p}D^-$	$<1.5 \times 10^{-5}$			[1]
$B^- \longrightarrow p\bar{p}D^{*-}$	$<1.5 \times 10^{-5}$			[1]
$B^- \longrightarrow \Lambda\bar{p}D^0$	$(1.43 \pm 0.32) \times 10^{-5}$			[1]
$B^- \longrightarrow \Lambda\bar{p}D^{*0}$	$<5 \times 10^{-5}$			[1]
$\bar{B}^0 \longrightarrow n\bar{p}D^{*+}$	$(1.4 \pm 0.4) \times 10^{-3}$			[1]
$\bar{B}^0 \longrightarrow p\bar{p}D^0$	$(1.04 \pm 0.07) \times 10^{-4}$			[1]
$\bar{B}^0 \longrightarrow p\bar{p}D^{*0}$	$(0.99 \pm 0.11) \times 10^{-4}$			[1]
$\bar{B}^0 \longrightarrow \Lambda\bar{p}D_s^+$	$(2.8 \pm 0.9) \times 10^{-5}$			[1]
$\bar{B}^0 \longrightarrow \Lambda\bar{p}D^+$	$(2.5 \pm 0.4) \times 10^{-5}$	-0.08 ± 0.10		[1, 13]
$\bar{B}^0 \longrightarrow \Lambda\bar{p}D^{*+}$	$(3.4 \pm 0.8) \times 10^{-5}$	$+0.55 \pm 0.17$		[1, 13]
$\bar{B}^0 \longrightarrow \Lambda\bar{\Lambda}\bar{D}^0$	$\left(1.00^{+0.30}_{-0.26}\right) \times 10^{-5}$			[1]
$\bar{B}^0 \longrightarrow \Sigma^0\bar{\Lambda}\bar{D}^0$+c.c.	$<3.1 \times 10^{-5}$			[1]

where $(\bar{q}q')$ and $(\bar{q}b)$ stand for the quark currents and the matrix element of $\langle \mathbf{B}\overline{\mathbf{B}'}|\bar{q}q'|0\rangle(\langle \mathbf{B}\overline{\mathbf{B}'}|(\bar{q}b|B\rangle)$ can be parameterized as the timelike baryonic (B to $\mathbf{B}\overline{\mathbf{B}'}$ transition) form factors $F_{\mathbf{B}\overline{\mathbf{B}'}}$. Moreover, one derives $F_{\mathbf{B}\overline{\mathbf{B}'}} \propto 1/t^n$ in perturbative QCD (pQCD) counting rules [17–24], where $t \equiv (p_{\mathbf{B}} + p_{\overline{\mathbf{B}'}})^2$ and n accounts for the number of the gluon propagators that attach to the baryon pair. It results in $d\mathscr{B}/dm_{\mathbf{B}\overline{\mathbf{B}'}} \propto 1/t^{2n}$, which shapes a peak around $m_{\mathbf{B}\overline{\mathbf{B}'}} \sim m_{\mathbf{B}} + m_{\mathbf{B}'}$ in the $m_{\mathbf{B}\overline{\mathbf{B}'}}$ spectrum, and then, the threshold effect can be interpreted. In the $B \longrightarrow p\bar{p}$ transition, there exists the term of $(p_{\bar{p}} - p_p)_\mu \bar{u}(\gamma_5)v$ for $F_{\mathbf{B}\overline{\mathbf{B}'}}$ [24], which is reduced as $(E_{\bar{p}} - E_p)\bar{u}(\gamma_5)v$ in the $p\bar{p}$ rest frame. Since $(E_{\bar{p}} - E_p) \propto \cos\theta_p$, the term for $F_{\mathbf{B}\overline{\mathbf{B}'}}$ can be used to describe the highly asymmetric $\mathscr{A}_{\mathrm{FB}}(B^- \longrightarrow p\bar{p}\pi^-, p\bar{p}K^-)$. Alternatively, the baryonic B decays is studied with the pole model, where the nonfactorizable contributions can be taken into account [25–28].

We have explained $\mathscr{B}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}) \sim 10^{-8} - 10^{-7}$ [29]. We have studied $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M$ and explained the branching fractions and CP asymmetries [30–38]. In addition, we have predicted $\mathscr{B}(\bar{B}^0_s \longrightarrow p\bar{\Lambda}K^- + \Lambda\bar{p}K^+) = (5.1 \pm 1.1) \times 10^{-6}$ [37], 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 [8]. This demonstrates that the theoretical approach can be reliable. Therefore, we would like to present a review, in order to illustrate how the approach of pQCD counting rules based on the factorization can be applied to the baryonic B decays. We will also review our theoretical results that have explained the branching fractions of $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$ and $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M$, particularly, the CP asymmetries, promising to be observed by future measurements.

2. Formalism

To review the two-body baryonic B decays, we take $\bar{B}^0 \longrightarrow p\bar{p}$ as our example. According to Figure 1, $\bar{B}^0 \longrightarrow p\bar{p}$ is regarded as an W-boson exchange process [29, 39–41]. In the factorization, we derive the amplitude as [29]

$$\mathscr{M}\left(\bar{B}^0 \longrightarrow p\bar{p}\right) = \frac{G_F}{\sqrt{2}} V_{ub}V^*_{ud}\, a_2 \left\langle p\bar{p}\middle|\bar{u}\gamma_\mu(1-\gamma_5)u\middle|0\right\rangle \left\langle 0\middle|\bar{d}\gamma^\mu(1-\gamma_5)b\middle|\bar{B}^0\right\rangle, \tag{3}$$

where G_F is the Fermi constant and $V^{(*)}_{ub(d)}$ the Cabibbo-Kobayashi-Maskawa (CKM) matrix element. One has defined $\langle 0|\bar{d}\gamma^\mu(1-\gamma_5)b|\bar{B}^0\rangle = -if_B q_\mu$ for the $\bar{B}^0$ meson annihilation, where f_B is the decay constant and q_μ the four-momentum. For the $p\bar{p}$ production, the matrix elements read [22, 23]

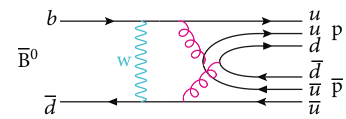

Figure 1: Feynman diagram for $\bar{B}^0 \longrightarrow p\bar{p}$.

$$\begin{aligned}\left\langle \mathbf{B}\overline{\mathbf{B}'}\middle|V_\mu\middle|0\right\rangle &= \bar{u}\left[F_1\gamma_\mu + \frac{F_2}{m_B + m_{\overline{B}'}} i\sigma_{\mu\nu}q_\mu\right]v,\\ \left\langle \mathbf{B}\overline{\mathbf{B}'}\middle|A_\mu\middle|0\right\rangle &= \bar{u}\left[g_A\gamma_\mu + \frac{h_A}{m_p + m_{\bar{p}}} q_\mu\right]\gamma_5 v,\end{aligned} \tag{4}$$

with the (axial-)vector current $V(A)_\mu = \bar{q}\gamma_\mu(\gamma_5)q'$, where $F_{1,2}$, g_A, and h_A are the timelike baryonic form factors.

At a very large momentum transfer ($Q^2 \longrightarrow \infty$), the approach of pQCD counting rules results in [17–21]

$$F_1, g_A \propto \frac{\alpha_s^2(Q^2)}{Q^4} \ln\left(\frac{Q^2}{\Lambda^2}\right)^{-(4/3\beta)}, \tag{5}$$

where $\beta = 11 - 2n_f/3$ is the β function of QCD to one loop, $n_f = 3$ the flavor number, and $\Lambda = 0.3\,\mathrm{GeV}$ the scale factor. Moreover, $\alpha_s(Q^2) \equiv (4\pi/\beta)[\ln(Q^2/\Lambda^2)]^{-1}$ is the running coupling constant in the strong interaction [20]. Interestingly, α_s^2/Q^4 reflects the fact that one needs two hard gluon propagators to attach to the baryons as drawn in Figure 1 [42], whereas $\ln(Q^2/\Lambda^2)^{-4/(3\beta)}$ is caused by the wave function.

As V_μ and A_μ are combined as the right- or left-handed chiral current, that is, $J^{R,L}_\mu = (V_\mu \pm A_\mu)/2$, one obtains $\langle \mathbf{B}'_{R+L}|J^{R(L)}_\mu|\mathbf{B}_{R+L}\rangle$ for the spacelike $\mathbf{B} \longrightarrow \mathbf{B}'$ transition. With the right-handed current, the matrix elements can be written as [19, 29]

$$\left\langle \mathbf{B}'_{R+L}\middle|J^R_\mu\middle|\mathbf{B}_{R+L}\right\rangle = \bar{u}\left[\gamma_\mu\frac{1+\gamma_5}{2}F_R + \gamma_\mu\frac{1-\gamma_5}{2}F_L\right]u, \tag{6}$$

where $|\mathbf{B}_{R+L}\rangle = |\mathbf{B}_R\rangle + |\mathbf{B}_L\rangle$ and $F_{R,L}$ are the chiral form factors. With q_i $(i = 1, 2, 3)$ denoting one of the valence quarks in $\mathbf{B}$, $Q \equiv J^R_{\mu=0}$ known as the chiral charge is able to change the flavor for q_i, such that $\mathbf{B}$ is transformed as $\mathbf{B}'$. Note that the chirality is regarded as the helicity at $Q^2 \longrightarrow \infty$. Since the helicity of q_i can be (anti-)parallel $[\|(\overline{\|})]$ to the helicity of $\mathbf{B}$, we define $Q_{\|(\overline{\|})}(i)$ that is responsible for acting on q_i. Thus, the approach of pQCD counting rules leads to [19, 29]

$$F_R = e^R_\| F_\| + e^R_{\overline{\|}} F_{\overline{\|}},\ F_L = e^L_\| F_\| + e^L_{\overline{\|}} F_{\overline{\|}}, \tag{7}$$

with $e^R_{\|(\overline{\|})} = \langle \mathbf{B}'_R|\mathbf{Q}_{\|(\overline{\|})}|\mathbf{B}_R\rangle$, $e^L_{\|(\overline{\|})} = \langle \mathbf{B}'_L|\mathbf{Q}_{\|(\overline{\|})}|\mathbf{B}_L\rangle$, and $\mathbf{Q}_{\|(\overline{\|})} = \sum_i Q_{\|(\overline{\|})}(i)$, where the SU(3) flavor ($\mathrm{SU}(3)_f$) and SU(2) spin symmetries are both respected. In the crossing

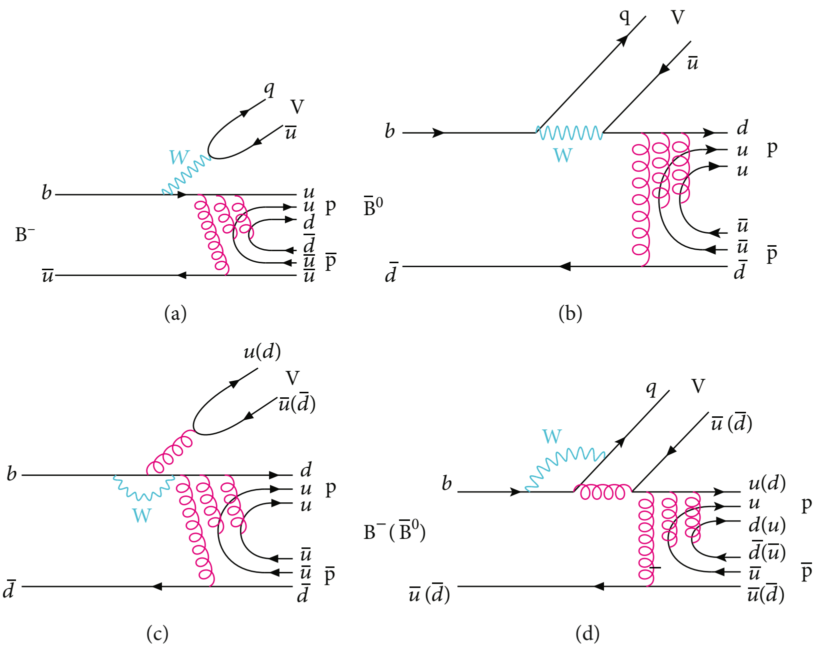

Figure 2: Feynman diagrams for $B \longrightarrow p\bar{p}V$.

symmetry, the spacelike form factors behave as the timelike ones, such that one can relate F_1 and g_A with the chiral form factors in Equations (6) and (7) derived in the spacelike region, leading to $F_1(g_A) = (e^R_{\parallel} \pm e^L_{\parallel})F_{\parallel} + (e^R_{\overline{\parallel}} \pm e^L_{\overline{\parallel}})F_{\overline{\parallel}}$. In addition to the momentum dependence of Equation (5), F_1 and g_A are presented as [22, 23, 29]

$$F_1 = \frac{C_{F_1}}{t^2} \ln\left(\frac{t}{\Lambda^2}\right)^{-\gamma}, g_A = \frac{C_{g_A}}{t^2} \ln\left(\frac{t}{\Lambda^2}\right)^{-\gamma}, \tag{8}$$

where $\gamma = 2 + 4/(3\beta) = 2.148$.

For $\langle p\bar{p}|\bar{u}u|0\rangle$, we obtain [23]

$$\begin{aligned} C_{F_1} &= \frac{5}{3}C_{\parallel} + \frac{1}{3}C_{\overline{\parallel}}, \\ C_{g_A} &= \frac{5}{3}C_{\parallel} - \frac{1}{3}C_{\overline{\parallel}}, \end{aligned} \tag{9}$$

where $C_{\parallel(\overline{\parallel})}$ is from $F_{\parallel(\overline{\parallel})} \equiv C_{\parallel(\overline{\parallel})}/t^2[\ln(t/\Lambda^2)]^{-\gamma}$, and we have used $(e^R_{\parallel}, e^L_{\parallel}) = (5/3, 0)$ and $(e^R_{\overline{\parallel}}, e^L_{\overline{\parallel}}) = (0, 1/3)$ [23, 29]. In Ref. [43], the pQCQ calculation causes $F_2 = F_1/(t\ln[t/\Lambda^2])$, indicating that F_2 has a suppressed contribution. Taking the form factors as the inputs, we reduce the amplitude of $\bar{B}^0 \longrightarrow p\bar{p}$ as

$$M \propto \frac{1}{(m_p + m_{\bar{p}})} \bar{u}\left[(m_p + m_{\bar{p}})^2 g_A + m_B^2 h_A\right]\gamma_5 v, \tag{10}$$

where $F_{1(2)}$ has been vanishing, in accordance with the conservation of vector current (CVC) $q^\mu\langle p\bar{p}|\bar{u}\gamma_\mu u|0\rangle = 0$. Using the partial conservation of axial-vector current (PCAC), where $q^\mu\langle \mathbf{B}\overline{\mathbf{B}'}|A_\mu|0\rangle = 0$, it is obtained that [23, 29, 39–41, 44]

$$h_A = -\frac{(m_B + m_{B'})^2 g_A}{t - m_M^2}, \tag{11}$$

by which g_A and h_A cancel each other and then $\mathscr{M} \simeq 0$. This seems that the W-exchange (annihilation) mechanism based on the factorization fails to explain $\mathscr{B}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'})$. As a consequence, one turns to think of the nonfactorizable effects as the main contributions [25, 44–50].

In Equation (11), $1/(t - m_M^2)$ describes a meson pole, so that $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$ can be regarded to receive the contribution from the intermediate process of $B \longrightarrow M \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$, which is much suppressed. On the other hand, there might exist a QCD-based contribution to h_A, by which $\mathscr{M}(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}) \neq 0$, and PCAC is violated. Here, we choose to parameterize h_A with slightly violated PCAC in the timelike region. To this end, we derive $h_A + g_A \simeq 0$ with $q^\mu\langle \mathbf{B}\overline{\mathbf{B}'}|A_\mu|0\rangle \simeq 0$ at the threshold area of $t \simeq (m_B + m_{\overline{B'}})^2$, where the meson pole is supposed to be inapplicable [40, 41]. Since the QCD-based calculation of h_A is still lacking, besides $h_A + g_A \simeq 0$ suggesting $h_A \propto g_A$, we are allowed to present $h_A = C_{h_A}/t^2$ for its momentum dependence [29].

To describe the three-body baryonic B decays, we take $B \longrightarrow p\bar{p}V$ with $V = \rho^{-(0)}$ or $K^{*-}(\bar{K}^{*0})$ as our examples. According to Figure 2, the amplitudes are given by [30–32]

$$\mathscr{M}(B \longrightarrow p\bar{p}V) \simeq \frac{G_F}{\sqrt{2}}\alpha_V\left\langle V\left|\bar{q}\gamma_\mu(1-\gamma_5)q'\right|0\right\rangle\left\langle p\bar{p}\left|\overline{q'}\gamma_\mu(1-\gamma_5)b\right|B\right\rangle, \tag{12}$$

Table 2: Theoretical results of the two- and three-body baryonic B decays, in comparison with the experimental data.

Decay mode	Experimental data [1, 2, 12]	Theory
$\mathcal{B}\left(\bar{B}^0 \longrightarrow p\bar{p}\right)$	$(1.25 \pm 0.32) \times 10^{-8}$	$(1.4 \pm 0.5) \times 10^{-8}$ [29]
$\mathcal{B}\left(\bar{B}^0 \longrightarrow \Lambda\bar{\Lambda}\right)$	$<3.2 \times 10^{-7}$	$(0.3 \pm 0.2) \times 10^{-8}$ [29]
$\mathcal{B}(B^- \longrightarrow \Lambda\bar{p})$	$\left(2.4^{+1.0}_{-0.9}\right) \times 10^{-7}$	$\left(3.5^{+0.7}_{-0.5}\right) \times 10^{-8}$ [29]
$\mathcal{B}\left(\bar{B}^0_s \longrightarrow p\bar{p}\right)$	$<1.5 \times 10^{-8}$	$\left(3.0^{+1.5}_{-1.2}\right) \times 10^{-8}$ [29]
$\mathcal{B}\left(\bar{B}^0 \longrightarrow p\bar{p}\pi^0\right)$	$(5.0 \pm 1.9) \times 10^{-7}$	$(5.0 \pm 2.1) \times 10^{-7}$ [31]
$\mathcal{B}\left(\bar{B}^0 \longrightarrow \Lambda\bar{\Lambda}\bar{K}^0\right)$	$\left(4.8^{+1.0}_{-0.9}\right) \times 10^{-6}$	$(2.5 \pm 0.3) \times 10^{-6}$ [33]
$\mathcal{B}(B^- \longrightarrow p\bar{p}\pi^-)$	$(1.62 \pm 0.20) \times 10^{-6}$	$(1.60 \pm 0.18) \times 10^{-6}$ [35]
$\mathcal{B}(B^- \longrightarrow \Lambda\bar{\Lambda}\pi^-)$	$<9.4 \times 10^{-7}$	$(1.7 \pm 0.7) \times 10^{-7}$ [33]
$\mathcal{B}(B^- \longrightarrow \Lambda\bar{\Lambda}K^-)$	$(3.4 \pm 0.6) \times 10^{-6}$	$(2.8 \pm 0.2) \times 10^{-6}$ [33]
$\mathcal{B}(\bar{B}^0_s \longrightarrow \bar{p}\Lambda K^+ + \text{c.c.})$	$(5.5 \pm 1.0) \times 10^{-6}$	$(5.1 \pm 1.1) \times 10^{-6}$ [37]
$\mathcal{B}\left(\bar{B}^0 \longrightarrow p\bar{p}\bar{K}^{*0}\right)$	$\left(1.24^{+0.28}_{-0.25}\right) \times 10^{-6}$	$(0.9 \pm 0.3) \times 10^{-6}$ [32]
$\mathcal{B}\left(\bar{B}^0 \longrightarrow \Lambda\bar{\Lambda}\bar{K}^{*0}\right)$	$\left(2.5^{+0.9}_{-0.8}\right) \times 10^{-6}$	$(1.76 \pm 0.18) \times 10^{-6}$ [36]
$\mathcal{B}(B^- \longrightarrow p\bar{p}K^{*-})$	$\left(3.6^{+0.8}_{-0.7}\right) \times 10^{-6}$	$(6.0 \pm 1.3) \times 10^{-6}$ [32]
$\mathcal{B}(B^- \longrightarrow \Lambda\bar{p}\rho^0, \rho^0 \longrightarrow \pi^+\pi^-)$	$(4.8 \pm 0.9) \times 10^{-6}$	$(3.28 \pm 0.31) \times 10^{-6}$ [36]
$\mathcal{B}(B^- \longrightarrow \Lambda\bar{p}\phi)$	$(8.0 \pm 2.2) \times 10^{-7}$	$(1.51 \pm 0.28) \times 10^{-6}$ [36]
$\mathcal{B}(B^- \longrightarrow \Lambda\bar{\Lambda}K^{*-})$	$\left(2.2^{+1.2}_{-0.9}\right) \times 10^{-6}$	$(1.91 \pm 0.20) \times 10^{-6}$ [36]
$\mathcal{A}_{\mathrm{FB}}\left(\bar{B}^0 \longrightarrow \Lambda\bar{p}\pi^+\right)$	$-0.41 \pm 0.11 \pm 0.03$	$\left(-14.6^{+0.9}_{-1.5} \pm 6.9\right) \times 10^{-2}$ [53]
$\mathcal{A}_{\mathrm{FB}}(B^- \longrightarrow \Lambda\bar{p}\pi^0)$	$-0.16 \pm 0.18 \pm 0.03$	$\left(-14.6^{+0.9}_{-1.5} \pm 6.9\right) \times 10^{-2}$ [53]
$\mathcal{A}_{\mathrm{FB}}(B^- \longrightarrow p\bar{p}\pi^-)$	$-0.409 \pm 0.033 \pm 0.006$	$\left(-49.1^{+0.6}_{-0.3} \pm 1.0 \pm 6.3\right) \times 10^{-2}$ [54]
$\mathcal{A}_{\mathrm{FB}}(B^- \longrightarrow p\bar{p}K^-)$	$0.495 \pm 0.012 \pm 0.007$	$\left(46.9^{+0.043}_{-0.041} \pm 0.2 \pm 4.7\right) \times 10^{-2}$ [54]
$\mathcal{A}_{\mathrm{CP}}(B^- \longrightarrow p\bar{p}\pi^-)$	0.00 ± 0.04	-0.06 [30]
$\mathcal{A}_{\mathrm{CP}}(B^- \longrightarrow p\bar{p}K^-)$	0.00 ± 0.04	0.06 ± 0.01 [30]
$\mathcal{A}_{\mathrm{CP}}(B^- \longrightarrow p\bar{p}K^{*-})$	0.21 ± 0.16	0.22 ± 0.04 [30]
$\mathcal{A}_{\mathrm{CP}}\left(\bar{B}^0 \longrightarrow p\bar{p}\pi^0\right)$		$(-16.8 \pm 5.4) \times 10^{-2}$ [31]
$\mathcal{A}_{\mathrm{CP}}\left(\bar{B}^0 \longrightarrow p\bar{p}\rho^0\right)$		$(-12.6 \pm 3.0) \times 10^{-2}$ [31]

with $q = (s, d)$ and $q' = u$ for $B^- \longrightarrow p\bar{p}(K^{*-}, \rho^-)$, and $q = (s, d)$ and $q' = d$ for $\bar{B}^0 \longrightarrow p\bar{p}(\bar{K}^{*0}, \rho^0)$. For α_V, we define

$$
\begin{aligned}
\alpha_{\rho^-} &= V_{ub}V_{ud}^* a_1 - V_{tb}V_{td}^* a_4, \\
\alpha_{\rho^0} &= V_{ub}V_{ud}^* a_2 + V_{tb}V_{td}^*\left(a_4 - \frac{3}{2}a_9\right), \\
\alpha_{K^{*-}} &= V_{ub}V_{us}^* a_1 - V_{tb}V_{ts}^* a_4, \\
\alpha_{\bar{K}^{*0}} &= -V_{tb}V_{ts}^* a_4.
\end{aligned} \tag{13}
$$

In Equation (12), one presents that $\langle V|\bar{q}\gamma_\mu(1-\gamma_5)q'|0\rangle = f_V m_V \varepsilon_\mu^*$, where f_V and ε_μ^* are, respectively, the decay constant and polarization four-vector of the vector meson. The amplitudes are both associated with the matrix elements of the $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$ transition, and we parameterize them as [24]

$$
\begin{aligned}
\left\langle \mathbf{B}\overline{\mathbf{B}'}\middle| V_\mu^b \middle| B\right\rangle &= i\bar{u}\left[g_1\gamma_\mu + g_2 i\sigma_{\mu\nu}p^\nu + g_3 p_\mu + g_4\left(p_{\overline{\mathbf{B}'}} + p_{\mathbf{B}}\right)_\mu \right.\\
&\quad \left. + g_5\left(p_{\overline{\mathbf{B}'}} - p_{\mathbf{B}}\right)_\mu\right]\gamma_5 v, \\
\left\langle \mathbf{B}\overline{\mathbf{B}'}\middle| A_\mu^b \middle| B\right\rangle &= i\bar{u}\left[f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}p^\nu + f_3 p_\mu + f_4\left(p_{\overline{\mathbf{B}'}} + p_{\mathbf{B}}\right)_\mu \right.\\
&\quad \left. + f_5\left(p_{\overline{\mathbf{B}'}} - p_{\mathbf{B}}\right)_\mu\right] v,
\end{aligned} \tag{14}
$$

Table 3: Theoretical results of the two- and three-body B decays with the baryon (meson) containing a charm quark, which are compared with the experimental data.

Decay mode	Experimental data [1, 13]	Theory
$\mathcal{B}(\bar{B}^0 \longrightarrow \Lambda_c^+ \bar{p})$	$(1.54 \pm 0.18) \times 10^{-5}$	$(1.0^{+0.4}_{-0.3}) \times 10^{-5}$ [57]
$\mathcal{B}(\bar{B}^0 \longrightarrow \Sigma_c^+ \bar{p})$	$<2.4 \times 10^{-5}$	$(2.9^{+0.8}_{-0.9}) \times 10^{-6}$ [57]
$\mathcal{B}(B^- \longrightarrow \Lambda \bar{p} D^0)$	$(1.43 \pm 0.32) \times 10^{-5}$	$(1.14 \pm 0.26) \times 10^{-5}$ [34]
$\mathcal{B}(B^- \longrightarrow \Lambda \bar{p} D^{*0})$	$<5 \times 10^{-5}$	$(3.23 \pm 0.32) \times 10^{-5}$ [34]
$\mathcal{B}(\bar{B}^0 \longrightarrow n \bar{p} D^{*+})$	$(1.4 \pm 0.4) \times 10^{-3}$	$(1.45 \pm 0.14) \times 10^{-3}$ [34]
$\mathcal{B}(\bar{B}^0 \longrightarrow p \bar{p} D^0)$	$(1.04 \pm 0.07) \times 10^{-4}$	$(1.04 \pm 0.12) \times 10^{-4}$ [38]
$\mathcal{B}(\bar{B}^0 \longrightarrow p \bar{p} D^{*0})$	$(0.99 \pm 0.11) \times 10^{-4}$	$(0.99 \pm 0.09) \times 10^{-4}$ [38]
$\mathcal{B}(\bar{B}^0 \longrightarrow \Lambda \bar{p} D^+)$	$(2.5 \pm 0.4) \times 10^{-5}$	$(1.85 \pm 0.30) \times 10^{-5}$ [38]
$\mathcal{B}(\bar{B}^0 \longrightarrow \Lambda \bar{p} D^{*+})$	$(3.4 \pm 0.8) \times 10^{-5}$	$(2.75 \pm 0.24) \times 10^{-5}$ [38]
$\mathcal{B}(\bar{B}^0 \longrightarrow \Sigma^0 \bar{\Lambda} \bar{D}^0 + c.c.)$	$<3.1 \times 10^{-5}$	$(1.8 \pm 0.5) \times 10^{-5}$ [34]
$\mathcal{A}_{\mathrm{FB}}(\bar{B}^0 \longrightarrow \Lambda \bar{p} D^+)$	-0.08 ± 0.10	-0.030 ± 0.002 [38]
$\mathcal{A}_{\mathrm{FB}}(\bar{B}^0 \longrightarrow \Lambda \bar{p} D^{*+})$	$+0.55 \pm 0.17$	$+0.150 \pm 0.000$ [38]

where $V_\mu^b(A_\mu^b) = \overline{q'}\gamma^\mu(\gamma_5)b$, $p = p_B - (p_{\overline{\mathbf{B}'}} + p_{\mathbf{B}})$, and (f_i, g_i) $(i = 1, 2, \cdots, 5)$ are the $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$ transition form factors. Inspired by pQCD counting rules [17, 18, 21, 23, 24], the momentum dependences for f_i and g_i are given by

$$f_i = \frac{D_{f_i}}{t^n}, g_i = \frac{D_{g_i}}{t^n}, \tag{15}$$

with $D_{f_i(g_i)}$ to be extracted by the data. According to the gluon lines in Figure 2, n in $1/t^n$ should be $2 + 1$, which accounts for two gluon propagators attaching to the valence quarks in $\mathbf{B}\overline{\mathbf{B}'}$ and an additional one for kicking (speeding up) the spectator quark in B [23]. For the gluon kicking, it is similar to the meson transition form factor derived as $F_M \propto 1/q^2$ in pQCD counting rules [20, 51], where $1/q^2$ is for a hard gluon to transfer the momentum to the spectator quark in the meson.

Like the case of F_1 and g_A, we relate (f_i, g_i) to the $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}$ chiral form factors, which is in terms of [23, 24]

$$\begin{aligned}\left\langle B_{R+L}\overline{B'}_{R+L}\right|\left(V_\mu^b + A_\mu^b\right)/2\left|B\right\rangle &= im_b\bar{u}\gamma_\mu\left[\frac{1+\gamma_5}{2}G_R + \frac{1-\gamma_5}{2}G_L\right]u \\ &+ i\bar{u}\gamma_\mu p_b\left[\frac{1+\gamma_5}{2}G_R^j + \frac{1-\gamma_5}{2}G_L^j\right]u,\end{aligned} \tag{16}$$

where $|B_q\rangle \sim |\bar{b}\gamma_5 q|0\rangle$ has been used. In addition, we obtain $G_{R(L)} = e_{\parallel}^{R(L)}G_{\parallel} + e_{\overline{\parallel}}^{R(L)}G_{\overline{\parallel}}$ and $G_{R(L)}^j = e_{\parallel}^{R(L)}G_{\parallel}^j + e_{\overline{\parallel}}^{R(L)}G_{\overline{\parallel}}^j$, which are similar to $F_{R,L}$ in Equation (7). Under the SU(3) flavor and SU(2) spin symmetries, together with $G_{\parallel(\overline{\parallel})}^{(j)} \equiv D_{\parallel(\overline{\parallel})}^{(j)}/t^n (j = 2, 3, \cdots, 5)$, it is derived that [23, 24]

$$\begin{aligned}D_{g_1} &= \frac{5}{3}D_{\parallel} - \frac{1}{3}D_{\overline{\parallel}}, \\ D_{f_1} &= \frac{5}{3}D_{\parallel} + \frac{1}{3}D_{\overline{\parallel}}, \\ D_{g_j} &= \frac{5}{3}D_{\parallel}^j = -D_{f_j}, \\ D_{g_1} &= \frac{1}{3}D_{\parallel} - \frac{2}{3}D_{\overline{\parallel}}, \\ D_{f_1} &= \frac{1}{3}D_{\parallel} + \frac{2}{3}D_{\overline{\parallel}}, \\ D_{g_j} &= \frac{-1}{3}D_{\parallel}^j = -D_{f_j},\end{aligned} \tag{17}$$

for $\langle p\bar{p}|\bar{u}b|B^-\rangle$ and $\langle p\bar{p}|\bar{d}b|\bar{B}^0\rangle$, respectively. We also review the direct CP asymmetry, defined by

$$\mathcal{A}_{\mathrm{CP}}\left(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M\right) \equiv \frac{\Gamma\left(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M\right) - \Gamma\left(\bar{B} \longrightarrow \bar{\mathbf{B}}\mathbf{B}'\bar{M}\right)}{\Gamma\left(B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M\right) + \Gamma\left(\bar{B} \longrightarrow \bar{\mathbf{B}}\mathbf{B}'\bar{M}\right)}, \tag{18}$$

where Γ denotes the decay width and $\bar{B} \longrightarrow \bar{\mathbf{B}}\mathbf{B}'\bar{M}$ the antiparticle decay.

3. Numerical Analysis

For the numerical analysis, we adopt the CKM matrix elements as [1]

$$\begin{gathered} V_{ub} = A\lambda^3(\rho - i\eta),\ V_{ud} = 1 - \lambda^2/2,\ V_{us} = \lambda, \\ V_{tb} = 1,\ V_{td} = A\lambda^3,\ V_{ts} = -A\lambda^2, \end{gathered} \tag{19}$$

with $\lambda = 0.22453 \pm 0.00044$, $A = 0.836 \pm 0.015$, $\bar{\rho} = 0.122^{+0.018}_{-0.017}$, and $\bar{\eta} = 0.355^{+0.012}_{-0.011}$ in the Wolfenstein parameterization, where $(\bar{\rho}, \bar{\eta}) = (1 - \lambda^2/2) \times (\rho, \eta)$. The decay constants are given by $(f_B, f_\rho, f_{K^*}) = (0.19, 0.21, 0.22)$ GeV [1, 52]. With the global fit to the data, we obtain [29, 37]

$$\begin{gathered} \left(C_{\|}, C_{\overline{\|}}, C_{h_A}\right) = (-102.4 \pm 7.3, 210.9 \pm 85.2, 8.4 \pm 1.4)\ \mathrm{GeV}^4, \\ \left(D_{\|}, D_{\overline{\|}}\right) = (45.7 \pm 33.8, -298.2 \pm 34.0)\ \mathrm{GeV}^5, \\ \left(D^2_{\|}, D^3_{\|}, D^4_{\|}, D^5_{\|}\right) = (33.1 \pm 30.7, -203.6 \pm 133.4, 6.5 \pm 18.1, \\ -147.1 \pm 29.3)\ \mathrm{GeV}^4. \end{gathered} \tag{20}$$

We take $a_i \equiv c_i^{\text{eff}} + c_{i\pm1}^{\text{eff}}/N_c$ for i =odd (even) with N_c the color number, where the effective Wilson coefficients c_i come from Ref. [16]. For a_2 in $\bar{B}^0 \longrightarrow p\bar{p}\rho^0$ and $\bar{B}^0 \longrightarrow p\bar{p}$, we use $N_c = 2$ to take into account the nonfactorizable QCD corrections. We can hence present our theoretical calculations for $B \longrightarrow p\bar{p}(V)$ in Table 2, along with the other $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M$ results. Besides, we present our studies of the angular and CP asymmetries.

4. Discussions and Conclusions

The theoretical results in Table 2 can agree well with the data, which is based on the factorization, pQCD counting rules, and baryonic form factors. In particular, several CP asymmetries are predicted as large as 10-20%, promising to be measured by LHCb and Belle II [55, 56]. It is reasonable to extend the theoretical approach to $B \longrightarrow \mathbf{B}_c\overline{\mathbf{B}'}$ and $B \longrightarrow \mathbf{B}\overline{\mathbf{B}'}M_c$ [34, 38, 57], where $\mathbf{B}_c(M_c)$ denotes a baryon (meson) containing a charm quark. As a consequence, $(\mathscr{B}, \mathscr{A}_{\text{FB}})$ can also be expalined (see Table 3). Nonetheless, $B(B^- \longrightarrow p\bar{p}\rho^-, \rho^- \longrightarrow \pi^-\pi^0) = (28.8 \pm 2.1) \times 10^{-6}$ and $\mathscr{B}(B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu) = (1.04 \pm 0.24 \pm 0.12) \times 10^{-4}$ we have predicted are not verified by the observations [1, 32, 58, 59],

$$\begin{gathered} \mathscr{B}\left(B^- \longrightarrow p\bar{p}\pi^-\pi^0\right) = (4.6 \pm 1.3) \times 10^{-6}, \\ \mathscr{B}\left(B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu\right) = \left(5.27^{+0.23}_{-0.24} \pm 0.21 \pm 0.15\right) \times 10^{-6}, \end{gathered} \tag{21}$$

where the amplitude of $B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu$ is given by

$$\mathscr{M}(B^- \longrightarrow p\bar{p}\ell\bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} V_{ub} \left\langle p\bar{p} \middle| \bar{u}\gamma_\mu(1-\gamma_5)b \middle| B^- \right\rangle \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell, \tag{22}$$

since $B \longrightarrow p\bar{p}\rho$ and $B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu$ are seen to be associated with the $B \longrightarrow p\bar{p}$ transition form factors, which are inferred to cause the overestimations. Besides, $\mathscr{B}(B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu)$ inconsistent with the data can be partly due to the inconsistent determination of $|V_{ub}|$ between the inclusive and exclusive B decays.

As the final remark, since the predictions of $\mathscr{B}(B^- \longrightarrow p\bar{p}\rho^-)$ and $\mathscr{B}(B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu)$ are shown to deviate from the observations by the factors of 6 and 20, respectively, the theoretical approach is facing some difficulties. Therefore, the reexamination should be performed elsewhere.

In summary, to review the baryonic B decays, we have summarized the experimental data, which includes branching fractions and angular and CP asymmetries. We have taken $\bar{B}^0 \longrightarrow p\bar{p}$ and $B \longrightarrow p\bar{p}V$ with $V = \rho^{-(0)}$ or $K^{*-}(\bar{K}^{*0})$ for theoretical illustration. We have also reviewed the CP asymmetries of $B \longrightarrow p\bar{p}M$, which can be used to compare with future measurements by LHCb and Belle II. With the theoretical results listed in the tables, we have demonstrated that the theoretical approach can be used to interpret most observations. Finally, we have also remarked that the theoretical approach has currently encountered some challenges in interpreting $\mathscr{B}(B^- \longrightarrow p\bar{p}\rho^-)$ and $\mathscr{B}(B^- \longrightarrow p\bar{p}\mu^-\bar{\nu}_\mu)$.

Data Availability

This manuscript has no associated data, or the data will not be deposited. The data used in this paper are publicly available, and they can be found in the corresponding references.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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