Baryonic $B$ meson decays

Xiaotao Huang,$^1$ Yu-Kuo Hsiao,$^2$ Jike Wang,$^1$ and Liang Sun$^3$,$^{†}$

$^1$The Institute for Advanced Studies, Wuhan University, Wuhan 430072, China
$^2$School of Physics and Information Engineering, Shanxi Normal University, Linfen 041004, China
$^3$School of Physics and Technology, Wuhan University, Wuhan 430072, China

(Dated: April 6, 2022)

Abstract

We review the two and three-body baryonic $B$ decays with the dibaryon ($B\bar{B}'$) 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 $B \rightarrow B\bar{B}'$ 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 $B \rightarrow B\bar{B}'M$, which are promising to be measured by the LHCb and Belle II experiments. Finally, we remark the theoretical challenges in interpreting $B(B^- \rightarrow p\bar{p}\rho^-)$ and $B(B^- \rightarrow p\bar{p}\mu^-\bar{\nu}_\mu)$. 

$^{∗}$Corresponding author: yukuohsiao@gmail.com
$^{†}$Corresponding author: Jike.Wang@whu.edu.cn
$^{‡}$Corresponding author: sunl@whu.edu.cn
I. 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 I. Typically, $\mathcal{B}(B \to B\bar{B}')$ is as small as $10^{-8} - 10^{-7}$. Nonetheless, it is observed that $\mathcal{B}(B \to B\bar{B}'M) \sim (10 - 100) \times \mathcal{B}(B \to B\bar{B}')$, due to a sharply rising peak in $B \to B\bar{B}'M$ observed around the threshold area of $m_{B\bar{B}'} \sim m_B + m_{\bar{B}'}$ in the dibaryon invariant mass spectrum [4]. Known as the threshold effect, it enhances $\mathcal{B}(B \to B\bar{B}'M)$ as large as $10^{-6}$. While the $B\bar{B}'$ production shows the tendency to occur around $m_{B\bar{B}'} \sim m_B + m_{\bar{B}'}$, $B \to B\bar{B}'$ proceeds at $m_B$ scale, far from the threshold area. This interprets the suppressed $\mathcal{B}(B \to B\bar{B}')$ [14, 15].

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

$$A_{FB} \equiv \frac{\mathcal{B}(\cos \theta_B > 0) - \mathcal{B}(\cos \theta_B < 0)}{\mathcal{B}(\cos \theta_B > 0) + \mathcal{B}(\cos \theta_B < 0)}. \quad (1)$$

In Table I, $A_{FB}(B^- \to p\bar{p}\pi^- , p\bar{p}K^-) = (-40.9 \pm 3.4, 49.5 \pm 1.4)\%$ [2] indicate that one of the dibaryon 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

$$\mathcal{M}(B \to B\bar{B}') \propto \langle B\bar{B}'|(\bar{q}q')|0\rangle \langle 0|(\bar{q}b)|B\rangle,$$
$$\mathcal{M}_1(B \to B\bar{B}'M) \propto \langle B\bar{B}'|(\bar{q}q')|0\rangle \langle M|(\bar{q}b)|B\rangle,$$
$$\mathcal{M}_2(B \to B\bar{B}'M) \propto \langle M|(\bar{q}q')|0\rangle \langle B\bar{B}'|(\bar{q}b)|B\rangle, \quad (2)$$

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

We have explained $\mathcal{B}(B \to BB') \sim 10^{-8} - 10^{-7}$ \cite{29}. We have studied $B \to BB'M$, and explained the branching fractions and $CP$ asymmetries \cite{30,38}. In addition, we have predicted $\mathcal{B}(B_s^0 \to p\bar{AA}K^- + \Lambda\bar{p}K^+) = (5.1 \pm 1.1) \times 10^{-6}$ \cite{37}, in excellent agreement with the

**TABLE I.** The measured branching fractions, forward-backward asymmetries ($A_{FB}$), and $CP$ asymmetries ($A_{CP}$) for the baryonic $B$ decays, where the notation $\dagger$ is for $A_{FB}$ with $m_{p\bar{p}} < 2.85$ GeV.

| Decay mode | Branching fraction | $A_{FB}$ | $A_{CP}$ | Ref |
|------------|--------------------|----------|----------|-----|
| $B^0 \to p\bar{p}$ | $(1.25 \pm 0.32) \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Lambda\bar{K}$ | $< 3.2 \times 10^{-7}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Lambda\bar{p}$ | $(2.4 \pm 0.9) \times 10^{-7}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to p\bar{p}$ | $< 1.5 \times 10^{-9}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to p\bar{p}\pi^0$ | $(5.0 \pm 1.9) \times 10^{-7}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to p\bar{p}\rho^0$ | $(2.60 \pm 0.32) \times 10^{-6}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Xi\pi^+$ | $(3.14 \pm 0.29) \times 10^{-6}$ | $-0.41 \pm 0.11 \pm 0.03$ | $0.04 \pm 0.07$ | \[1,12\] |
| $B^0 \to \Xi\rho^+$ | $< 3.8 \times 10^{-7}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Lambda K^+$ | $< 8.2 \times 10^{-7}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Lambda K^0$ | $(4.8 \pm 1.0) \times 10^{-6}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to p\bar{p}K^-$ | $(1.62 \pm 0.20) \times 10^{-6}$ | $( -0.409 \pm 0.033 \pm 0.006 )^\dagger$ | $0.00 \pm 0.04$ | \[1,2\] |
| $B^- \to p\bar{p}K^*$ | $(5.9 \pm 0.5) \times 10^{-6}$ | $(0.495 \pm 0.012 \pm 0.007)^\dagger$ | $0.00 \pm 0.04$ | \[1,2\] |
| $B^- \to \Lambda\rho^+$ | $(3.0 \pm 0.7) \times 10^{-6}$ | $-0.16 \pm 0.18 \pm 0.03$ | $0.01 \pm 0.17$ | \[1,13\] |
| $B^- \to \Lambda\rho^0$ | $< 9.4 \times 10^{-7}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to \Lambda K^-$ | $(3.4 \pm 0.6) \times 10^{-6}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to \Lambda K^0$ | $(5.5 \pm 1.0) \times 10^{-6}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to p\bar{p}\rho^{*+}$ | $(1.24^{+0.26}_{-0.22}) \times 10^{-6}$ | $0.05 \pm 0.12$ | \[1\] |
| $B^0 \to \Lambda\Lambda^{*+}$ | $(2.5^{+0.9}_{-0.8}) \times 10^{-6}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to p\bar{p}\rho^{*-}$ | $(3.6^{+0.8}_{-0.7}) \times 10^{-6}$ | $0.21 \pm 0.16$ | \[1\] |
| $B^- \to \Lambda\rho^0, \rho^0 \to \pi^+\pi^-$ | $(4.8 \pm 0.9) \times 10^{-6}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to \Lambda\phi$ | $(8.0 \pm 2.2) \times 10^{-7}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to \Lambda K^{*-}$ | $(2.2^{+1.1}_{-0.7}) \times 10^{-6}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Lambda\bar{p}$ | $(1.54 \pm 0.18) \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Sigma^*_+\bar{p}$ | $< 2.4 \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to \Sigma^*_0\bar{p}$ | $(2.9 \pm 0.7) \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to p\bar{p}D^-$ | $< 1.5 \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to p\bar{p}D^{*-}$ | $< 1.5 \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to \Lambda\rho D^0$ | $(1.43 \pm 0.32) \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^- \to \Lambda\rho D^{*-0}$ | $< 5 \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \rho D^+$ | $(1.4 \pm 0.4) \times 10^{-3}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \rho D^0$ | $(1.04 \pm 0.07) \times 10^{-4}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \rho D^{*-0}$ | $(0.99 \pm 0.11) \times 10^{-4}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Lambda p D^+$ | $(2.8 \pm 0.9) \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Lambda p D^{*+}$ | $(2.5 \pm 0.4) \times 10^{-5}$ | $-0.08 \pm 0.10$ | \[1,13\] |
| $B^0 \to \Lambda\rho D^{*+}$ | $(3.4 \pm 0.8) \times 10^{-5}$ | $+0.55 \pm 0.17$ | \[1,13\] |
| $B^0 \to \Lambda\bar{K} D^0$ | $(1.00^{+0.30}_{-0.20}) \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
| $B^0 \to \Sigma^0\Lambda D^0 + c.c.$ | $< 3.1 \times 10^{-5}$ | \[1\] | \[1\] | \[1\] |
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 \(B \to BB'\) and \(B \to BB'M\); particularly, the \(CP\) asymmetries, promising to be observed by future measurements.

II. FORMALISM

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

\[
\mathcal{M}(\bar{B}^0 \to p\bar{p}) = \frac{G_F}{\sqrt{2}} V_{ub} V_{ud}^* a_2 \langle p\bar{p}|\bar{u}\gamma_\mu(1-\gamma_5)u|0\rangle \langle 0|\bar{d}\gamma^\mu(1-\gamma_5)b|\bar{B}^0\rangle, 
\]

(3)

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

\[
\langle BB'|V_\mu|0\rangle = \bar{u} \left[ F_1 \gamma_\mu + \frac{F_2}{m_B + m_B'} i\sigma_{\mu\nu} q_\nu \right] v, \\
\langle BB'|A_\mu|0\rangle = \bar{u} \left[ g_A \gamma_\mu + \frac{h_A}{m_p + m_\bar{p}} q_\mu \right] \gamma_5 v, 
\]

(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 \((Q^2 \rightarrow \infty)\), the approach of pQCD counting rules results in\(\frac{C_1}{17}\),\(\frac{C_2}{21}\)

\[
F_1, g_A \propto \frac{\alpha_s^2(Q^2)}{Q^4} \ln \left( \frac{Q^2}{\Lambda^2} \right)^{-\frac{1}{3\beta}},
\]

where \(\beta = 11 - 2n_f/3\) is the \(\beta\) function of QCD to one loop, \(n_f = 3\) the flavor number, and \(\Lambda = 0.3\) 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\(\frac{C_3}{20}\). Interestingly, \(\alpha_s^2/Q^4\) reflects the fact that one needs two hard gluon propagators to attach to the baryons as drawn in Fig.\(\frac{C_4}{42}\), whereas \(\ln(Q^2/\Lambda^2)^{-4/(3\beta)}\) is caused by the wave function.

As \(V_\mu\) and \(A_\mu\) are combined as the right or left-handed chiral current, that is, \(J_{\mu}^{R,L} = (V_\mu \pm A_\mu)/2\), one obtains \(\langle B_{R+L} | J_{\mu}^{R,L} | B_{R+L} \rangle\) for the spacelike \(B \rightarrow B'\) transition. With the right-handed current, the matrix elements can be written as\(\frac{C_5}{19}\),\(\frac{C_6}{29}\)

\[
\langle B'_{R+L} | J_{\mu}^{R} | B_{R+L} \rangle = \bar{u} \left[ \gamma^R_{\mu} \frac{1 + \gamma^5}{2} F_R + \gamma^L_{\mu} \frac{1 - \gamma^5}{2} F_L \right] u,
\]

where \(|B_{R+L}\rangle = |B_R\rangle + |B_L\rangle\), and \(F_{R,L}\) are the chiral form factors. With \(q_i\) \((i = 1, 2, 3)\) denoting one of the valence quarks in \(B\), \(Q \equiv J_{\mu=0}^{R,L}\) known as the chiral charge is able to change the flavor for \(q_i\), such that \(B\) is transformed as \(B'\). Note that the chirality is regarded as the helicity at \(Q^2 \rightarrow \infty\). Since the helicity of \(q_i\) can be (anti-)parallel \(\| (\|)\) to the helicity of \(B\), we define \(Q_{\| (\|)}(i)\) that is responsible for acting on \(q_i\). Thus, the approach of pQCD counting rules lead to\(\frac{C_7}{14}\),\(\frac{C_8}{29}\)

\[
F_R = e^R_{\|} F_{\|} + e^R_{\|} F_{\|}, \quad F_L = e^L_{\|} F_{\|} + e^L_{\|} F_{\|},
\]

with \(e^R_{\| (\|)} = \langle B'_{R} | Q_{\| (\|)} | B_{R} \rangle, e^L_{\| (\|)} = \langle B'_{L} | Q_{\| (\|)} | B_{L} \rangle\) and \(Q_{\| (\|)} = \sum_i Q_{\| (\|)}(i)\), where the \(SU(3)\) flavor \((SU(3)_f)\) and \(SU(2)\) spin symmetries are both respected. In the crossing 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 Eqs.\(\frac{C_9}{5}\),\(\frac{C_{10}}{7}\) derived in the spacelike region, leading to \(F_1(g_A) = (e^R_{\|} \pm e^L_{\|}) F_{\|} + (e^R_{\|} \pm e^L_{\|}) F_{\|}\). In addition to the momentum dependence of Eq.\(\frac{C_{11}}{5}\), \(F_1\) and \(g_A\) are presented as\(\frac{C_{12}}{22}\),\(\frac{C_{13}}{23}\),\(\frac{C_{14}}{29}\)

\[
F_1 = \frac{C_F}{t^2} \ln \left( \frac{t}{\Lambda^2} \right)^{-\gamma}, \quad g_A = \frac{C_{g_A}}{t^2} \ln \left( \frac{t}{\Lambda^2} \right)^{-\gamma},
\]

where \(\gamma = 2 + 4/(3\beta) = 2.148\).
For $\langle p\bar{p}|(u\bar{u})|0\rangle$, we obtain \[23\]

$$C_{F_1} = \frac{5}{3} C_{||} + \frac{1}{3} C_{||}, \quad C_{g_A} = \frac{5}{3} C_{||} - \frac{1}{3} C_{||},$$

(9)

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

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

(10)

where $F_1(2)$ has been vanishing, in accordance with the conservation of vector current (CVC) $q^\mu \langle p\bar{p}|u\gamma_\mu u|0\rangle = 0$. Using the partial conservation of axial-vector current (PCAC), where $q^\mu \langle B\bar{B}'|A_\mu|0\rangle = 0$, it is obtained that \[23, 29, 39-41, 44\],

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

(11)

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

In Eq. (11), $1/(t - m_M^2)$ describes a meson pole, so that $B \to B\bar{B}'$ can be regarded to receive the contribution from the intermediate process of $B \to M \to B\bar{B}'$, which is much suppressed. On the other hand, there might exist a QCD-based contribution to $h_A$, by which $\mathcal{M}(B \to B\bar{B}') \neq 0$, 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 $q^\mu \langle B\bar{B}'|A_\mu|0\rangle \simeq 0$ at the threshold area of $t \simeq (m_B + m_{B'})^2$, where the meson pole is supposed to be inapplicable \[40, 41\]. Since the QCD-based calculation of $h_A$ is still lacking, besides $h_A + g_A \simeq 0$ suggests $h_A \propto g_A$, 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 $B \to p\bar{p}V$ with $V = \rho^{(0)}$ or $K^{*-}(\bar{K}^{*0})$ as our examples. According to Fig. \[2\] the amplitudes are given by \[30, 32\]

$$\mathcal{M}(B \to p\bar{p}V) \simeq \frac{G_F}{\sqrt{2}} \alpha_V \langle V|\bar{q} \gamma_\mu (1 - \gamma_5) q|0\rangle \langle p\bar{p}|q' \gamma_\mu (1 - \gamma_5)b|B\rangle,$$

(12)
FIG. 2. Feynman diagrams for $B \to p\bar{p}V$.

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

$$
\alpha_V = V_{ub}V_{ud}^* a_1 - V_{tb}V_{td}^* a_4, \\
\alpha_{\rho} = V_{ub}V_{ud}^* a_2 + V_{tb}V_{td}^* (a_4 - \frac{3}{2} a_9), \\
\alpha_{K^{*-}} = V_{ub}V_{us}^* a_1 - V_{tb}V_{ts}^* a_4, \\
\alpha_{\bar{K}^{*0}} = -V_{tb}V_{ts}^* a_4.
$$

(13)

In Eq. (12), one presents that

$$
\langle V|q\gamma_\mu(1 - \gamma_5)q'|0\rangle = f_V m_V \varepsilon^*_\mu, \\
\langle B\bar{B}'|A_{b}\mu|B\rangle = i\bar{u}[g_1\gamma_\mu + g_2 i \sigma_{\mu\nu} p^\nu + g_3 p_{\mu} + g_4 (p_{\bar{B}} - p_{B})_{\mu} + g_5 (p_{\bar{B}} - p_{B})_{\mu}]\gamma_5 v,
$$

$$
\langle B\bar{B}'|A_{b}^h|B\rangle = i\bar{u}[f_1\gamma_\mu + f_2 i \sigma_{\mu\nu} p^\nu + f_3 p_{\mu} + f_4 (p_{\bar{B}} - p_{B})_{\mu} + f_5 (p_{\bar{B}} - p_{B})_{\mu}] v,
$$

(14)

where $V^b_{\mu}(A^h_{\mu}) = q'\gamma^\mu(\gamma_5)b$, $p = p_B - (p_{\bar{B}} + p_B)$, and $(f_i, g_i)$ ($i = 1, 2, \ldots, 5$) are the $B \to B\bar{B}'$ 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

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

(15)
with \( D_{f_i(g_i)} \) to be extracted by the data. According to the gluon lines in Fig. 2, \( n \) in \( 1/t^n \) should be \( 2+1 \), which accounts for two gluon propagators attaching to the valence quarks in \( B \bar{B}' \) and an additional one for kicking (speeding up) the spectator quark in \( B \) \cite{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 \cite{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 \( B \rightarrow B \bar{B}' \) chiral form factors, which is in terms of \cite{23,24}

\[
\langle B_{R+L} \bar{B}'_{R+L} | (V^b_{\mu} + A^b_{\mu})/2 | B \rangle =
\]

\[
im_b \bar{u} \gamma_{\mu} \left[ \frac{1 + \gamma_5}{2} G_R + \frac{1 - \gamma_5}{2} G_L \right] u + i \bar{u} \gamma_{\mu} \not{p}_b \left[ \frac{1 + \gamma_5}{2} G_R + \frac{1 - \gamma_5}{2} G_L \right] u,
\]

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

\[
D_{g_1} = \frac{5}{3} D_{\|} - \frac{1}{3} D_{\|}, \quad D_{f_1} = \frac{5}{3} D_{\|} + \frac{1}{3} D_{\|}, \quad D_{g_2} = \frac{5}{3} D_{\|} = -D_{f_2},
\]

\[
D_{g_1} = \frac{1}{3} D_{\|} - \frac{2}{3} D_{\|}, \quad D_{f_1} = \frac{1}{3} D_{\|} + \frac{2}{3} D_{\|}, \quad D_{g_2} = \frac{1}{3} D_{\|} = -D_{f_2},
\]

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

\[
A_{CP}(B \rightarrow B \bar{B}' M) \equiv \frac{\Gamma(B \rightarrow B \bar{B}' M) - \Gamma(B \rightarrow \bar{B} B' M)}{\Gamma(B \rightarrow B \bar{B}' M) + \Gamma(B \rightarrow \bar{B} B' M)},
\]

where \( \Gamma \) denotes the decay width, and \( \bar{B} \rightarrow \bar{B} B' M \) the anti-particle decay.

**III. NUMERICAL ANALYSIS**

For the numerical analysis, we adopt the CKM matrix elements as \cite{1}

\[
V_{ub} = A \lambda^3 (\rho - i \eta), V_{ud} = 1 - \lambda^2/2, V_{us} = \lambda,
\]

\[
V_{tb} = 1, V_{td} = A \lambda^3, V_{ts} = -A \lambda^2,
\]

with \( \lambda = 0.22453 \pm 0.00044, A = 0.836 \pm 0.015, \rho = 0.122^{+0.018}_{-0.017}, \eta = 0.355^{+0.012}_{-0.011} \) in the Wolfenstein parameterization, where \((\rho, \eta) = (1 - \lambda^2/2) \times (\rho, \eta)\). The decay constants are
TABLE II. Theoretical results of the two and three-body baryonic $B$ decays, in comparison with the experimental data.

| Decay mode            | Exp’st data $[1, 2, 12]$ | Theory            |
|-----------------------|--------------------------|-------------------|
| $\bar{B}^0 \to \bar{p}p\bar{p}$ | $(1.25 \pm 0.32) \times 10^{-8}$ | $(1.4 \pm 0.5) \times 10^{-8}$ |
| $\bar{B}^0 \to \Lambda\Lambda$ | $< 3.2 \times 10^{-7}$ | $(0.3 \pm 0.2) \times 10^{-8}$ |
| $B^- \to \Lambda\Lambda$ | $(2.4^{+1.0}_{-0.9}) \times 10^{-7}$ | $(3.5^{+0.7}_{-0.5}) \times 10^{-8}$ |
| $B^+ \to pp\bar{p}$ | $< 1.5 \times 10^{-8}$ | $(3.0^{+1.5}_{-1.2}) \times 10^{-9}$ |
| $\bar{B}^0 \to pp\bar{p}$ | $(5.0 \pm 1.9) \times 10^{-7}$ | $(5.0 \pm 2.1) \times 10^{-7}$ |
| $\bar{B}^0 \to \Lambda\Lambda\bar{K}$ | $(4.8^{+1.0}_{-0.9}) \times 10^{-6}$ | $(2.5 \pm 0.3) \times 10^{-6}$ |
| $B^- \to pp\pi^-$ | $(1.62 \pm 0.20) \times 10^{-6}$ | $(1.60 \pm 0.18) \times 10^{-6}$ |
| $B^- \to \Lambda\pi^-$ | $< 9.4 \times 10^{-7}$ | $(1.7 \pm 0.7) \times 10^{-7}$ |
| $B^- \to \Lambda\pi^-$ | $(3.4 \pm 0.6) \times 10^{-6}$ | $(2.8 \pm 0.2) \times 10^{-6}$ |
| $\bar{B}^0 \to \Lambda\Lambda\bar{K}$ | $(5.5 \pm 1.0) \times 10^{-6}$ | $(5.1 \pm 1.1) \times 10^{-6}$ |
| $\bar{B}^0 \to \Lambda\Lambda\bar{K}$ | $(1.4^{+0.25}_{-0.25}) \times 10^{-6}$ | $(0.9 \pm 0.3) \times 10^{-6}$ |
| $\bar{B}^0 \to \Lambda\Lambda\bar{K}$ | $(2.5^{+0.9}_{-0.9}) \times 10^{-6}$ | $(1.76 \pm 0.18) \times 10^{-6}$ |
| $B^- \to pp\bar{K}^*$ | $(3.6^{+0.8}_{-0.7}) \times 10^{-6}$ | $(6.0 \pm 1.3) \times 10^{-6}$ |
| $B^- \to \Lambda\pi^+ \pi^-$ | $(4.8 \pm 0.9) \times 10^{-6}$ | $(3.28 \pm 0.31) \times 10^{-6}$ |
| $B^- \to \Lambda\phi$ | $(8.0 \pm 2.2) \times 10^{-7}$ | $(1.51 \pm 0.28) \times 10^{-6}$ |
| $B^- \to \Lambda\phi$ | $(2.2^{+1.2}_{-1.2}) \times 10^{-6}$ | $(1.91 \pm 0.20) \times 10^{-6}$ |
| $A_{FB}(\bar{B}^0 \to \Lambda\Lambda\bar{K})$ | $-0.41 \pm 0.11 \pm 0.03$ | $(-14.6^{+0.9}_{-1.5} \pm 6.9) \times 10^{-2}$ |
| $A_{FB}(B^- \to \Lambda\Lambda\bar{K})$ | $-0.16 \pm 0.18 \pm 0.03$ | $(-14.6^{+0.9}_{-1.5} \pm 6.9) \times 10^{-2}$ |
| $A_{FB}(B^- \to \Lambda\Lambda\bar{K})$ | $-0.409 \pm 0.033 \pm 0.006$ | $(-49.1^{+0.6}_{-0.3} \pm 1.0 \pm 6.3) \times 10^{-2}$ |
| $A_{FB}(B^- \to \Lambda\Lambda\bar{K})$ | $0.495 \pm 0.012 \pm 0.007$ | $(46.9^{+0.043}_{-0.041} \pm 0.2 \pm 4.7) \times 10^{-2}$ |
| $A_{CP}(\bar{B}^0 \to pp\bar{K}^-)$ | $0.00 \pm 0.04$ | $-0.06 \pm 0.04$ |
| $A_{CP}(B^- \to pp\bar{K}^-)$ | $0.00 \pm 0.04$ | $0.06 \pm 0.04$ |
| $A_{CP}(B^- \to pp\bar{K}^-)$ | $0.21 \pm 0.16$ | $0.22 \pm 0.04$ |
| $A_{CP}(\bar{B}^0 \to pp\bar{K}^-)$ | $(-16.8 \pm 5.4) \times 10^{-2}$ | |
TABLE III. 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 | Exp’t data [1, 13] | Theory |
|------------|--------------------|--------|
| $B(B^0 \to \Lambda^0 p)$ | $(1.54 \pm 0.18) \times 10^{-5}$ | $(1.0^{+0.4}_{-0.3}) \times 10^{-5}$ [55] |
| $B(B^0 \to \Sigma^+_n p)$ | $< 2.4 \times 10^{-5}$ | $(2.9^{+0.8}_{-0.9}) \times 10^{-6}$ [55] |
| $B(B^- \to \Lambda\bar{p}B^0)$ | $(1.43 \pm 0.32) \times 10^{-5}$ | $(1.14 \pm 0.26) \times 10^{-5}$ [34] |
| $B(B^- \to \Lambda\bar{p}D^{*0})$ | $< 5 \times 10^{-5}$ | $(3.23 \pm 0.32) \times 10^{-5}$ [34] |
| $B(B^0 \to n\bar{p}D^{++})$ | $(1.4 \pm 0.4) \times 10^{-3}$ | $(1.45 \pm 0.14) \times 10^{-3}$ [34] |
| $B(B^0 \to n\bar{p}D^0)$ | $(1.04 \pm 0.07) \times 10^{-4}$ | $(1.04 \pm 0.12) \times 10^{-4}$ [34] |
| $B(B^0 \to n\bar{p}D^{*0})$ | $(0.99 \pm 0.11) \times 10^{-4}$ | $(0.99 \pm 0.09) \times 10^{-4}$ [34] |
| $B(B^0 \to \Lambda\bar{p}D^+)$ | $(2.5 \pm 0.4) \times 10^{-5}$ | $(1.85 \pm 0.30) \times 10^{-5}$ [34] |
| $B(B^0 \to \Lambda\bar{p}D^{*+})$ | $(3.4 \pm 0.8) \times 10^{-5}$ | $(2.75 \pm 0.24) \times 10^{-5}$ [34] |
| $B(B^0 \to \Sigma^0\Lambda\bar{D}^0 + c.c.)$ | $< 3.1 \times 10^{-5}$ | $(1.8 \pm 0.5) \times 10^{-5}$ [34] |
| $A_{FB}(B^0 \to \Lambda\bar{p}D^+)$ | $-0.08 \pm 0.10$ | $-0.030 \pm 0.002$ [34] |
| $A_{FB}(B^0 \to \Lambda\bar{p}D^{*+})$ | $+0.55 \pm 0.17$ | $+0.150 \pm 0.000$ [34] |

Asymmetries are predicted as large as 10-20%, promising to be measured by LHCb and Belle II [56, 57]. It is reasonable to extend the theoretical approach to $B \to B_c \bar{B}'$ and $B \to B\bar{B}'M_c$ [34, 38, 55], where $B_c(M_c)$ denotes a baryon (meson) containing a charm quark. As a consequence, $(\mathcal{B}, A_{FB})$ can also be explained (see Table III). Nonetheless, $\mathcal{B}(B^- \to p\bar{p}\rho^-, \rho^- \to \pi^-\pi^0) = (28.8 \pm 2.1) \times 10^{-6}$ and $\mathcal{B}(B^- \to p\bar{p}\mu^+\mu^-) = (1.04 \pm 0.24 \pm 0.12) \times 10^{-4}$ we have predicted are not verified by the observations [1, 32, 58, 59],

$$\mathcal{B}(B^- \to p\bar{p}\rho^-) = (4.6 \pm 1.3) \times 10^{-6},$$

$$\mathcal{B}(B^- \to p\bar{p}\mu^+\mu^-) = (5.27^{+0.33}_{-0.24} \pm 0.21 \pm 0.15) \times 10^{-6},$$

(21)

where the amplitude of $B^- \to p\bar{p}\mu^+\mu^-$ is given by

$$\mathcal{M}(B^- \to p\bar{p}\ell\bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} V_{ub} \langle p\bar{p} | \bar{u} \gamma_\mu (1 - \gamma_5) b | B^- \rangle \bar{\ell} \gamma_\mu (1 - \gamma_5) \nu_\ell .$$

(22)

Since $B \to p\bar{p}\rho$ and $B^- \to p\bar{p}\mu^+\mu^-$ are seen to be associated with the $B \to p\bar{p}$ transition form factors, which are inferred to cause the overestimations. Besides, $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu)$ 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 $\mathcal{B}(B^- \to p\bar{p}\rho^-)$ and $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu)$ are shown to deviate from the observations by the factors of 6 and 20, respectively, the theoretical approach is facing some difficulties. Therefore, the re-examination should be performed elsewhere.
In summary, to review the baryonic $B$ decays, we have summarized the experimental data, which includes branching fractions, angular and $CP$ asymmetries. We have taken $\bar{B}^0 \rightarrow p\bar{p}$ and $B \rightarrow p\bar{p}V$ with $V = \rho^{-(0)}$ or $K^{*-}(K^{*0})$ for theoretical illustration. We have also reviewed the $CP$ asymmetries of $B \rightarrow p\bar{p}M$, 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 $\mathcal{B}(B^- \rightarrow p\bar{p}\rho^-)$ and $\mathcal{B}(B^- \rightarrow p\bar{p}\mu^-\bar{\nu}_\mu)$.

**ACKNOWLEDGMENTS**

The authors would like to thank Professors Xin Liu, Zhen-Jun Xiao, Qin Chang, and Rui-Lin Zhu for inviting us to write a review article on the physics of baryonic $B$ meson decays in the special issue “Heavy Flavor Physics and CP Violation” of Advances in High Energy Physics. YKH was supported in part by NSFC (Grant Nos. 11675030 and 12175128). LS was supported in part by NSFC (Grant No. 12061141006) and Joint Large-Scale Scientific Facility Funds of the NSFC and CAS (Grant No. U1932108).

[1] P.A. Zyla et al. [Particle Data Group], “Review of Particle Physics,” PTEP 2020, 083C01 (2020).
[2] R. Aaij et al. [LHCb], “Evidence for CP Violation in $B^+ \rightarrow p\bar{p}K^+$ Decays,” Phys. Rev. Lett. 113, 141801 (2014).
[3] K. Abe et al. [Belle], “Observation of $B^\pm \rightarrow p\bar{p}K^\pm$,” Phys. Rev. Lett. 88, 181803 (2002).
[4] B. Aubert et al. [BaBar], “Measurement of the $B^+ \rightarrow p\bar{p}K^+$ branching fraction and study of the decay dynamics,” Phys. Rev. D 72, 051101 (2005).
[5] B. Aubert et al. [BaBar], “Measurements of the Decays $B^0 \rightarrow \bar{D}^0 p\bar{p}$, $B^0 \rightarrow \bar{D}^{*0} p\bar{p}$, $B^0 \rightarrow D^- p\bar{p}\pi^+$, and $B^0 \rightarrow D^{*-} p\bar{p}\pi^+$,” Phys. Rev. D 74, 051101 (2006).
[6] J.T. Wei et al. [Belle], “Study of $B^+ \rightarrow p\bar{p}K^+$ and $B^+ \rightarrow p\bar{p}\pi^+$,” Phys. Lett. B 659, 80 (2008).
[7] J.H. Chen et al. [Belle], “Observation of $B^0 \rightarrow p\bar{p}K^{*0}$ with a large $K^{*0}$ polarization,” Phys. Rev. Lett. 100, 251801 (2008).

[8] R. Aaij et al. [LHCb], “First observation of a baryonic $B^0_s$ decay,” Phys. Rev. Lett. 119, 041802 (2017).

[9] R. Aaij et al. [LHCb], “First Observation of the Rare Purely Baryonic Decay $B^0 \rightarrow p\bar{p}$,” Phys. Rev. Lett. 119, 232001 (2017).

[10] R. Aaij et al. [LHCb], “Evidence for the two-body charmless baryonic decay $B^+ \rightarrow p\bar{\Lambda}$,” JHEP 04, 162 (2017).

[11] R. Aaij et al. [LHCb], “Studies of the decays $B^+ \rightarrow p\bar{p}h^+$ and observation of $B^+ \rightarrow \bar{\Lambda}(1520)p$,” Phys. Rev. D 88, 052015 (2013).

[12] M.Z. Wang et al. [Belle], “Study of $B^+ \rightarrow p\bar{\Lambda}\gamma$, $p\bar{\Lambda}\pi^0$ and $B^0 \rightarrow p\bar{\Lambda}\pi^-$,” Phys. Rev. D 76, 052004 (2007).

[13] Y.Y. Chang et al. [Belle], “Observation of $B^0 \rightarrow p\Lambda D^{(*)-}$,” Phys. Rev. Lett. 115, 221803 (2015).

[14] W.S. Hou and A. Soni, “Pathways to rare baryonic B decays,” Phys. Rev. Lett. 86, 4247 (2001).

[15] M. Suzuki, “Partial waves of baryon-antibaryon in three-body B meson decay,” J. Phys. G 34, 283 (2007).

[16] A. Ali, G. Kramer, and C.D. Lu, “Experimental tests of factorization in charmless nonleptonic two-body B decays,” Phys. Rev. D 58, 094009 (1998).

[17] S.J. Brodsky and G.R. Farrar, “Scaling Laws at Large Transverse Momentum,” Phys. Rev. Lett. 31, 1153 (1973).

[18] S.J. Brodsky and G.R. Farrar, “Scaling Laws for Large Momentum Transfer Processes,” Phys. Rev. D 11, 1309 (1975).

[19] G.P. Lepage and S.J. Brodsky, “Exclusive Processes in Quantum Chromodynamics: The Form-Factors of Baryons at Large Momentum Transfer,” Phys. Rev. Lett. 43, 545; 1625(E) (1979).

[20] G.P. Lepage and S.J. Brodsky, “Exclusive Processes in Perturbative Quantum Chromodynamics,” Phys. Rev. D 22, 2157 (1980).

[21] S.J. Brodsky, C.E. Carlson, J.R. Hiller and D.S. Hwang, “Single spin polarization effects and the determination of time-like proton form-factors,” Phys. Rev. D 69, 054022 (2004).
C.K. Chua, W.S. Hou and S.Y. Tsai, “Understanding $B \to D^*N\bar{N}$ and its implications,” Phys. Rev. D 65, 034003 (2002).

C.K. Chua, W.S. Hou and S.Y. Tsai, “Charmless three-body baryonic $B$ decays,” Phys. Rev. D 66, 054004 (2002).

C.Q. Geng and Y.K. Hsiao, “Angular distributions in three-body baryonic $B$ decays,” Phys. Rev. D 74, 094023 (2006).

H.Y. Cheng and K.C. Yang, “Charmless exclusive baryonic $B$ decays,” Phys. Rev. D 66, 014020 (2002).

H.Y. Cheng and K.C. Yang, “Three body charmed baryonic $B$ decays $\bar{B} \to D^{(*)}N\bar{N}$,” Phys. Rev. D 66, 094009 (2002).

H.Y. Cheng and K.C. Yang, “Charmful baryonic $B$ decays $\bar{B}_0 \to \Lambda_c\bar{p}$ and $\bar{B} \to \Lambda_c\bar{p}\pi(\rho)$,” Phys. Rev. D 65, 054028 (2002); 65, 099901(E) (2002).

H.Y. Cheng, “Exclusive baryonic $B$ decays circa 2005,” Int. J. Mod. Phys. A 21, 4209 (2006).

Y.K. Hsiao and C.Q. Geng, “Violation of partial conservation of the axial-vector current and two-body baryonic $B$ and $D_s$ decays,” Phys. Rev. D 91, 077501 (2015).

C.Q. Geng, Y.K. Hsiao and J.N. Ng, “Direct CP violation in $B^\pm \to ppK^{*\pm}$,” Phys. Rev. Lett. 98, 011801 (2007).

Y.K. Hsiao, S.Y. Tsai and E. Rodrigues, “Direct CP violation in internal W-emission dominated baryonic $B$ decays,” Eur. Phys. J. C 80, 565 (2020).

C.Q. Geng, Y.K. Hsiao and J.N. Ng, “Study of $B \to ppK^*$ and $B \to pp\rho$,” Phys. Rev. D 75, 094013 (2007).

C.Q. Geng and Y.K. Hsiao, “Study of $B \to \Lambda\bar{\Lambda}K$ and $B \to \Lambda\bar{\Lambda}\pi$,” Phys. Lett. B 619, 305 (2005).

C.H. Chen, H.Y. Cheng, C.Q. Geng and Y.K. Hsiao, “Charmful Three-body Baryonic $B$ decays,” Phys. Rev. D 78, 054016 (2008).

Y.K. Hsiao and C.Q. Geng, “Determination of $|V_{ub}|$ from exclusive baryonic $B$ decays,” Phys. Lett. B 755, 418 (2016).

C.Q. Geng and Y.K. Hsiao, “Study of $\bar{B} \to \Lambda\bar{p}\rho(\phi)$ and $\bar{B} \to \Lambda\bar{\Lambda}\bar{K}^*$,” Phys. Rev. D 85, 017501 (2012).

C.Q. Geng, Y.K. Hsiao and E. Rodrigues, “Three-body charmless baryonic $\bar{B}_s^0$ decays,” Phys. Lett. B 767, 205 (2017).
[38] Y.K. Hsiao and C.Q. Geng, “Factorization and angular distribution asymmetries in charming baryonic $B$ decays,” Phys. Rev. D 93, 034036 (2016).

[39] I. Bediaga and E. Predazzi, “On the Decay $D_s^+ \rightarrow p\bar{n}$,” Phys. Lett. B 275, 161 (1992).

[40] X.Y. Pham, “A Beautiful Signature $F^+ \rightarrow p\bar{n}$ as an Unambiguous Proof of the Annihilation Mechanism,” Phys. Rev. Lett. 45, 1663 (1980).

[41] X.Y. Pham, “Partial Conservation of Axial Current (PCAC) and the Decay of Charmed $F$ Meson Into a Nucleon Pair,” Phys. Lett. 94B, 231 (1980).

[42] M. Ambrogiani et al. [E835], “Measurements of the magnetic form-factor of the proton in the timelike region at large momentum transfer,” Phys. Rev. D 60, 032002 (1999).

[43] A Perturbative QCD analysis of the nucleon’s Pauli form-factor $F(2)(Q^2)$, A.V. Belitsky, X.D. Ji and F. Yuan, Phys. Rev. Lett. 91, 092003 (2003).

[44] C.H. Chen, H.Y. Cheng and Y.K. Hsiao, “Baryonic $D$ Decay $D_s^+ \rightarrow p\bar{n}$ and Its Implication,” Phys. Lett. B 663, 326 (2008).

[45] V.L. Chernyak and I.R. Zhitnitsky, “$B$ meson exclusive decays into baryons,” Nucl. Phys. B 345, 137 (1990).

[46] P. Ball and H.G. Dosch, “Branching ratios of exclusive decays of bottom mesons into baryon-anti-baryon pairs,” Z. Phys. C 51, 445 (1991).

[47] C.H.V. Chang and W.S. Hou, “$B$ meson decays to baryons in the diquark model,” Eur. Phys. J. C 23, 691 (2002).

[48] C.K. Chua, “Charmless Two-body Baryonic $B_{u,d,s}$ Decays Revisited,” Phys. Rev. D 89, 056003 (2014).

[49] X.G. He, T. Li, X.Q. Li and Y.M. Wang, “Calculation of BR($\bar{B}^0 \rightarrow \Lambda_c^+ + \bar{p}$) in the PQCD approach,” Phys. Rev. D 75, 034011 (2007).

[50] H.Y. Cheng and K.C. Yang, “Hadronic $B$ decays to charmed baryons,” Phys. Rev. D 67, 034008 (2003).

[51] C.K. Chua, W.S. Hou, S.Y. Shiau and S.Y. Tsai, “Evidence for factorization in three-body $\bar{B} \rightarrow D^{(*)}K^-K^0$ decays,” Phys. Rev. D 67, 034012 (2003).

[52] X. Huang, Y.K. Hsiao, J. Wang and L. Sun, “Angular asymmetries in $B \rightarrow \Lambda\bar{p}M$ decays,” arXiv:2201.07717 [hep-ph].

[53] Y.K. Hsiao, “Angular asymmetry in charmless $B \rightarrow p\bar{p}M$ decays,” in preparation.
[54] P. Ball and R. Zwicky, “$B_{d,s} \to \rho, \omega, K^*, \phi$ decay form factors from light-cone sum rules revisited,” Phys. Rev. D 71, 014029 (2005).

[55] Y.K. Hsiao, S.Y. Tsai, C.C. Lih and E. Rodrigues, “Testing the W-exchange mechanism with two-body baryonic $B$ decays,” JHEP 04, 035 (2020).

[56] E. Kou et al. [Belle II], “The Belle II Physics Book,” PTEP 2019, 123C01 (2019); 2020, 029201(E) (2020).

[57] E. Kou et al. [Belle II], “The Belle II Physics Book,” PTEP 2019, 123C01 (2019); 2020, 029201(E) (2020).

[58] C.Q. Geng and Y.K. Hsiao, “Semileptonic $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ decays,” Phys. Lett. B 704, 495 (2011).

[59] R. Aaij et al. [LHCb], “Observation of the semileptonic decay $B^+ \to \bar{p}\mu^+\nu_\mu$,” JHEP 03, 146 (2020).