Semileptonic $B$ decays with $B$ to $B\bar{B}'$ transition

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Abstract

We study the semileptonic $B \to B\bar{B}'L\bar{L}'$ decays with $B\bar{B}'$ ($L\bar{L}'$) representing a baryon (lepton) pair. Using the new determination of the $B \to B\bar{B}'$ transition form factors, we present $\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (5.4 \pm 2.0) \times 10^{-6}$ agreeing with the current data. Besides, $\mathcal{B}(B^- \to \Lambda\bar{\nu}\nu) = (3.5 \pm 1.0) \times 10^{-8}$ is calculated to be 20 times smaller than the previous prediction. In particular, we predict $\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda} e^-\bar{\nu}_e, p\bar{\Lambda} \mu^-\bar{\nu}_\mu, p\bar{\Lambda} e^-\bar{\nu}_e) = (2.1 \pm 0.6, 2.1 \pm 0.6, 1.7 \pm 1.0) \times 10^{-6}$ and $\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{\Lambda}\nu\bar{\nu}) = (0.8 \pm 0.2) \times 10^{-8}$, which can be accessible to the LHCb experiment.
I. INTRODUCTION

In the three-body baryonic $B$ decays, the observation of $B \rightarrow p\bar{p}(\pi, K^{(*)}, D^{(*)})$ and $B^{-} \rightarrow \Lambda\bar{p}(J/\psi, \gamma)$ suggests the unique existence of the $B \rightarrow B\bar{B}'$ transition \cite{1,2}, with which the predictions for the $CP$ asymmetries of $B^{-} \rightarrow p\bar{p}(\pi, K^{(*)})$ \cite{3,4} and the branching fractions of $B^{-} \rightarrow \Lambda\bar{p}D^{(*)0}$, $\bar{B}^{0} \rightarrow \Sigma^{0}\Lambda D^{0}$ \cite{5,6} have been verified by the later measurements \cite{7}.

The semileptonic $B$ decays of $B^{-} \rightarrow p\bar{p}\ell^{-}\bar{\nu}_{\ell}$ and $B^{-} \rightarrow \Lambda\bar{p}\nu_{\ell}\bar{\nu}_{\ell}$ with $\ell$ denoting $e$, $\mu$ or $\tau$ can provide another direct evidence for the $B \rightarrow B\bar{B}'$ transition \cite{8,9}. Like the studies of the semileptonic $B^{-} \rightarrow \pi^{+}\pi^{-}\ell^{-}\bar{\nu}_{\ell}$ decays \cite{10,11}, the full invariant dibaryon mass spectrum can be used to investigate the possible co-existence of the resonant and non-resonant contributions. Therefore, we have predicted $\mathcal{B}(B^{-} \rightarrow p\bar{p}\mu^{-}\bar{\nu}_{\mu}) = (1.04 \pm 0.26 \pm 0.12) \times 10^{-4}$ \cite{8} and $\mathcal{B}(B^{-} \rightarrow \Lambda\bar{p}\nu_{\ell}\bar{\nu}_{\ell}) = (7.9 \pm 1.9) \times 10^{-7}$ \cite{9}. We have also predicted that $\mathcal{R}_{e/\mu} \equiv \mathcal{B}(B^{-} \rightarrow p\bar{p}\ell^{-}\bar{\nu}_{\ell}) / \mathcal{B}(B^{-} \rightarrow p\bar{p}\mu^{-}\bar{\nu}_{\mu}) \simeq 1$ \cite{8}. By contrast, the pole model argument leads to the evaluation of $\mathcal{B}(B \rightarrow B\bar{B}'\ell_{\ell}) = 10^{-5} - 10^{-6}$ \cite{10}.

Experimentally, one has measured that \cite{13,14,15}

$$
\mathcal{B}_{ex}(B^{-} \rightarrow p\bar{p}\ell^{-}\bar{\nu}_{\ell}) = (5.8 \pm 3.7 \pm 3.6) \times 10^{-4} \ (< 1.2 \times 10^{-3}) \ [\text{Cleo}],
$$
$$
\mathcal{B}_{ex}(B^{-} \rightarrow p\bar{p}\ell^{-}\bar{\nu}_{\ell}) = (8.2^{+3.7}_{-3.2} \pm 0.6) \times 10^{-6} \ [\text{Belle}],
$$
$$
\mathcal{B}_{ex}(B^{-} \rightarrow p\bar{p}\mu^{-}\bar{\nu}_{\mu}) = (3.1^{+3.1}_{-2.4} \pm 0.7) \times 10^{-6} \ [\text{Belle}],
$$
$$
\mathcal{B}_{ex}(B^{-} \rightarrow p\bar{p}\mu^{-}\bar{\nu}_{\mu}) = (5.27^{+0.23}_{-0.24} \pm 0.21 \pm 0.15) \times 10^{-6} \ [\text{LHCb}],
$$
$$
\mathcal{B}_{ex}(B^{-} \rightarrow \Lambda\bar{p}\nu_{\ell}\bar{\nu}_{\ell}) = (0.4 \pm 1.1 \pm 0.6) \times 10^{-5} \ (< 3.0 \times 10^{-5}) \ [\text{Babar}].
$$

The threshold effect commonly observed in $B \rightarrow B\bar{B}'M$ is also observed in $B^{-} \rightarrow p\bar{p}\mu^{-}\bar{\nu}_{\mu}$ \cite{15}, which is drawn as the peak rising around the threshold area of $m_{B\bar{B}'} \simeq m_{B} + m_{\bar{B}'}$ in the $B\bar{B}'$ invariant mass spectrum. There is no sign that the $B$ meson transition to $B\bar{B}'$ receives a resonant contribution. Nonetheless, it is clearly seen that $\mathcal{B}_{ex}(B^{-} \rightarrow p\bar{p}\mu^{-}\bar{\nu}_{\mu})$ is 20 times smaller than the prediction of Ref. \cite{8}. This has been pointed out as the theoretical challenge to alleviate the discrepancy \cite{17}. On the other hand, the ratio $\mathcal{R}_{e/\mu} \simeq 1$ as a test of the lepton universality is not conclusive, and the prediction of $\mathcal{B}(B^{-} \rightarrow \Lambda\bar{p}\nu_{\ell}\bar{\nu}_{\ell})$ is within the experimental upper bound.

The overestimation for $\mathcal{B}(B^{-} \rightarrow p\bar{p}\ell^{-}\bar{\nu}_{\ell})$ is due to the fact that the $B \rightarrow B\bar{B}'$ transition form factors ($F_{B\bar{B}'}$) are extracted from the measured three-body baryonic $B$ decays \cite{6}, that is, the decay rates of $\bar{B}^{0} \rightarrow p\bar{p}D^{0}$, $B^{-} \rightarrow p\bar{p}K^{*-}$, $\bar{B}^{0} \rightarrow p\bar{p}K^{*0}$, and $B^{-} \rightarrow p\bar{p}\pi^{-}$, and the
angular asymmetry of $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$. With the same extraction, $\mathcal{B}(B^- \to \Lambda\bar{p}\nu\bar{\nu})$ might be overestimated. We hence propose to newly extract $F_{\bar{B}B}$, in order that $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ and $B_s^- \to \Lambda\bar{p}\nu\bar{\nu}$ can be simultaneously interpreted; besides, re-investigating $B^- \to \Lambda\bar{p}\nu\bar{\nu}$. Since LHCb has been able to accumulate more events for the $\bar{B}_s^0$ decays, we will study $\bar{B}_s^0 \to p\Lambda\bar{p}\nu\bar{\nu}$ and $\bar{B}_s^0 \to \Lambda\bar{\Lambda}\nu\bar{\nu}$ decays for future measurements.

II. FORMALISM

According to the effective Hamiltonians for $b \to u\ell^-\bar{\nu}_\ell$ and $b \to s\nu\ell\bar{\nu}_\ell$ decays, the semileptonic $B \to \bar{B}B'LL'$ decays with $LL' = (\ell^-\bar{\nu}_\ell, \nu\ell\bar{\nu}_\ell)$ and $\ell = (e, \mu, \tau)$ can be derived as

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

$$\mathcal{M}(B \to \bar{B}B'\nu_\ell\bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} \frac{\alpha_{em}}{2\pi\sin^2\theta_W} \lambda_\ell D(x_\ell) \langle \bar{B}B'|\bar{s}\gamma_\mu(1-\gamma_5)b|B\rangle \bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\nu_\ell,$$  \hspace{1cm} (2)

where $G_F$ is the Fermi constant, and $|V_{ub}|$ and $\lambda_\ell \equiv V_{ts}^\ast V_{tb}$ are the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements. With $x_\ell \equiv m_\ell^2/m_W^2$, $D(x_\ell)$ is the function for the top-quark loop integration. As depicted in Fig. 1, $B^- \to p\bar{p}\ell\bar{\nu}, \Lambda\bar{p}\nu\bar{\nu}$ and $\bar{B}_s^0 \to p\Lambda\nu\bar{\nu}, \Lambda\Lambda\nu\bar{\nu}$ can occur as the specific decay processes for our study.

FIG. 1. Feynman diagrams for the $B \to \bar{B}B'LL'$ decays, where (a) depicts $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ and $B_s^0 \to p\Lambda\ell^-\bar{\nu}_\ell$, while (b,c) $B^- \to \Lambda\bar{p}\nu\bar{\nu}$ and $\bar{B}_s^0 \to \Lambda\bar{\Lambda}\nu\bar{\nu}$. The diagrams show the process of leptonic decays with the lepton and antilepton states as ($\ell^-\bar{\nu}_\ell, \nu\ell\bar{\nu}_\ell$) and ($\ell^-\bar{\nu}_\ell, \nu\ell\bar{\nu}_\ell$), respectively.
Using the $B \to B\bar{B}'$ transition form factors, one is able to relate the semileptonic $B^- \to B\bar{B}'LL'$ decays to the three-body baryonic $B$ decay channels $B \to p\bar{p}M_c$, whose amplitudes are given by

$$
\mathcal{M}(B \to p\bar{p}M_c) = \frac{G_F}{\sqrt{2}} \left[ \alpha_1^q \langle M | q' q \gamma_{\mu} (1 - \gamma_5) u \rangle \langle p\bar{p} | q q' \gamma^\mu (1 - \gamma_5) b | B \rangle + \alpha_2^q \langle M_c | \bar{c} \gamma_{\mu} (1 - \gamma_5) u \rangle \langle p\bar{p} | \bar{d} \gamma^\mu (1 - \gamma_5) b | B \rangle \right],
$$

with $M = (\pi, \rho, K^{(*)})$ and $M_c = D^{(*)}$. We hence obtain $\mathcal{M}(B^- \to p\bar{p}\pi^-, p\bar{p}\rho^-)$ with $(q, q') = (u, d)$ and $\mathcal{M}(B^- \to p\bar{p}K^-, p\bar{p}K^*)$ with $(q, q') = (u, s)$, where $\alpha_1^q = V_{ub} V_{ud}^* a_1 - V_{tb} V_{ts}^* a_4$ and $\alpha_2^q = V_{ub} V_{td}^* 2a_6$. With $(q, q') = (d, s)$, we obtain $\mathcal{M}(\bar{B}^0 \to p\bar{p}K^{(*)})$, where $\alpha_1^s = -V_{tb} V_{ts}^* a_4$ and $\alpha_2^s = V_{tb} V_{ts}^* 2a_6$. For $\mathcal{M}(\bar{B}^0 \to p\bar{p}M_c)$, it is given that $\alpha_2^s = V_{cb} V_{ud}^* a_2$. The factorization approach derives that $a_i = c_i^{\text{eff}} + c_i^{\text{eff}}/N_c$ for $i = \text{odd}$ (even), where $c_i^{\text{eff}}$ are the effective Wilson coefficients, and $N_c$ the color number.

The matrix elements of the $B \to B\bar{B}'$ transition in Eqs. (2) and (3) can be presented as

$$
\langle B\bar{B}' | q | q' \rangle = i \bar{u} [g_1 \gamma_{\mu} + g_2 i \sigma_{\mu\nu} p^\nu + g_3 p_{\mu} + g_4 (p_B + p_{\bar{B}})_\mu + g_5 (p_B - p_{\bar{B}})_\mu] \gamma_5 v,
\langle B\bar{B}' | q | q' \rangle = i \bar{u} [f_1 \gamma_{\mu} + f_2 i \sigma_{\mu\nu} p^\nu + f_3 p_{\mu} + f_4 (p_B + p_{\bar{B}})_\mu + f_5 (p_B - p_{\bar{B}})_\mu] v,
\langle B\bar{B}' | q | q' \rangle = i \bar{u} [\bar{g}_1 \phi + \bar{g}_2 (E_B + E_{\bar{B}}) + \bar{g}_3 (E_B - E_{\bar{B}})] \gamma_5 v,
\langle B\bar{B}' | q | q' \rangle = i \bar{u} [\bar{f}_1 \phi + \bar{f}_2 (E_B + E_{\bar{B}}) + \bar{f}_3 (E_B - E_{\bar{B}})] v,
$$

where $p_{\mu} = (p_B - p_{\bar{B}} - p_{\bar{B}}')_\mu$, and $F_{B\bar{B}'} \equiv (g_i, f_i, \bar{g}_j, \bar{f}_j)$ with $i = 1, 2, ..., 5$ and $j = 1, 2, 3$ are the $B \to B\bar{B}'$ transition form factors. In terms of perturbative QCD counting rules, one parameterizes that

$$
f_i = \frac{D_{f_i}}{t^3}, \quad g_i = \frac{D_{g_i}}{t^3},
\bar{f}_j = \frac{D_{\bar{f}_j}}{t^3}, \quad \bar{g}_j = \frac{D_{\bar{g}_j}}{t^3},
$$

with $t \equiv (p_B + p_{\bar{B}})^2$. For $F_{B\bar{B}'} \sim 1/t^n$, $n = 2 + 1$ corresponds to the three gluon propagators. As seen in Fig. the two gluons provide the valence quarks in $B\bar{B}'$, and the other one speeds up the spectator quark in the $B$ meson. Since $V_{\mu}^b = \bar{q} \gamma_{\mu} b$ and $A_{\mu}^b = \bar{q} \gamma_{\mu} \gamma_5 b$ can be combined as the right-handed chiral current $R_{\mu} = (V_{\mu}^b + A_{\mu}^b)/2$, and the baryon decomposed of the
right and left-handed states, that is, $|B_{R+L}\rangle = |B_R\rangle + |B_L\rangle$, it leads to $\langle B_{R+L}|\bar{B'}_{R+L}|R_\mu|B\rangle = \langle B_R|\bar{B'}_R|R_\mu|B\rangle = \langle B_L|\bar{B'}_L|R_\mu|B\rangle$. Likewise, we perform a derivation for $\bar{B'}$. We hence obtain $G_{R,L}^{(k)}$ as the $B \to \bar{B}\bar{B'}$ transition form factors in the chiral representation. Furthermore, we derive that

$$
G_{R(L)} \propto e_{R(L)}^{(R(L))} G_{||} + e_{R(L)}^{(R(L))} G_{||},
$$

(7)

where $e_{||}^{R(L)}$ and $e_{||}^{R(L)}$ sum over the weight factors of $B_{R(L)}\bar{B'}_{R(L)}$, and $e_{R(L)}^{(R(L))}$ and $e_{R(L)}^{(R(L))}$ those of $B_{R(L)}\bar{B'}_{R(L)}$, while the helicity of $\bar{q}_i$ can be (anti-)parallel $[||]$ to the helicity of $\bar{B'}$. Note that the chirality has been regarded as the helicity at $t \to \infty$. By defining $G_{||}^{(k)} = D_{||}^{(k)} / t^3$ ($k = 2, 3, ..., 5$), we relate the two sorts of the form factors as $[1, 3, 22]$

$$
D_{g_1} = \frac{5}{3} D_{||} - \frac{1}{3} D_{\perp}, \quad D_{f_1} = \frac{5}{3} D_{||} + \frac{1}{3} D_{\perp}, \quad D_{g_k} = \frac{4}{3} D_{k} = -D_{f_k},
$$

(8)

for $\langle p\bar{p}|(\bar{u}b)|B^-\rangle$, $\langle p\bar{p}|(\bar{d}b)|\bar{B}^0\rangle$, $\langle \Lambda\bar{p}|(\bar{s}b)_{V,A}|B^-\rangle$, $\langle p\Lambda|(\bar{u}b)|\bar{B}^0\rangle$, and $\langle \Lambda\Lambda|(\bar{d}b)|\bar{B}^0\rangle$, respectively. Likewise, we perform a derivation for $\bar{g}_j$ ($\bar{f}_j$) through the (pseudo-)scalar current, which leads to $[22, 23]$

$$
D_{\bar{g}_1} = \frac{5}{3} \bar{D}_{||} - \frac{1}{3} \bar{D}_{\perp}, \quad D_{\bar{f}_1} = \frac{5}{3} \bar{D}_{||} + \frac{1}{3} \bar{D}_{\perp}, \quad D_{\bar{g}_{2,3}} = \frac{4}{3} \bar{D}_{2,3} = -D_{f_{2,3}},
$$

(9)

for $\langle p\bar{p}|(\bar{u}b)|B^-\rangle$ and $\langle p\bar{p}|(\bar{d}b)|\bar{B}^0\rangle$, respectively.

For the four-body $B(p_B) \to B(p_B')\bar{B}'(p_B')L(p_L)\bar{L}'(p_{L'})$ decay, there are five kinematic variables in the phase space, that is, $s \equiv (p_L + p_{L'})^2 \equiv m_{L,L'}^2$, $t$, and $(\theta_B, \theta_L, \phi) \[28–30\]$. As
depicted in Fig. 2, the angle $\theta$ is the angle between the meson and baryon moving directions in the meson rest frame, respectively. The partial decay width then reads \cite{8, 9}

$$d\Gamma = \frac{|\mathcal{M}|^2}{4(4\pi)^6m_B^2}X\alpha_B\alpha_L\,ds\,dt\,dcos\theta_B\,dcos\theta_L\,d\phi,$$

where $X = [(m_B^2 - s - t)^2/4 - st]^{1/2}$, $\alpha_B = \lambda^{1/2}(t, m_B^2, m_B^2)/t$, and $\alpha_L = \lambda^{1/2}(s, m_L^2, m_L^2)/s$, with $\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ac - 2bc - 2ca$. For integration, the allowed ranges of the five variables are $(m_L + m_{L'})^2 \leq s \leq (m_B - \sqrt{t})^2$, $(m_B + m_B')^2 \leq t \leq (m_B - m_L - m_{L'})^2$, $0 \leq \theta_{B,L} \leq \pi$, and $0 \leq \phi \leq 2\pi$. The partial decay width of $B(p_B) \rightarrow B(p_B')\bar{B}'(p_{B'})M(p_M)$ involves two variables in the phase space, given by \cite{3, 22}

$$d\Gamma = \frac{\beta_B^{1/2}\beta_t^{1/2}}{(8\pi m_B)^3}|\mathcal{M}|^2\,dt\,dcos\theta,$$

where $\beta_B = [1-(m_B + m_B')^2/t][1-(m_B - m_B')^2/t]$, $\beta_t = [(m_B + m_M)^2 - t][(m_B - m_M)^2 - t]$, and $\theta$ is the angle between the meson and baryon moving directions in the $\bar{B}\bar{B}'$ rest frame. The allowed regions of the variables are $-1 < \cos\theta < 1$ and $(m_B + m_B')^2 < t < (m_B - m_M)^2$.

For the global fit in the next section, we define the $CP$ asymmetry \cite{4, 31}, and angular asymmetries for $B \rightarrow \bar{B}\bar{B}'M \cite{3, 22, 32}$ and $B \rightarrow \bar{B}\bar{B}'LL' \cite{8, 9}$, written as

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

$$A_{FB,\theta_i} \equiv \frac{\Gamma(\cos\theta_i > 0) - \Gamma(\cos\theta_i < 0)}{\Gamma(\cos\theta_i > 0) + \Gamma(\cos\theta_i < 0)},$$

where $\bar{B} \rightarrow \bar{B}\bar{B}'\bar{M}$ represents the anti-particle decay.
TABLE I. The effective Wilson coefficients $c_i^{eff}$ ($i = 1, \ldots, 6$) for $b$ and $\bar{b}$ decays.

| $c_i^{eff}$ | $b \to d$ ($b \to \bar{d}$) | $b \to s$ ($b \to \bar{s}$) |
|-------------|-----------------|-----------------|
| $c_1^{eff}$ | 1.168 (1.168)   | 1.168 (1.168)   |
| $c_2^{eff}$ | $-0.365 (-0.365)$ | $-0.365 (-0.365)$ |
| $10^3 c_3^{eff}$ | $238.0 + 12.7i (257.4 + 46.1i)$ | $243.3 + 31.2i (240.9 + 32.3i)$ |
| $10^4 c_4^{eff}$ | $-497.0 - 38.6i (-555.2 - 138.3i) - 512.8 - 94.7i (-505.7 - 96.8i)$ |
| $10^5 c_5^{eff}$ | $145.5 + 12.7i (164.7 + 46.1i)$ | $150.7 + 31.2i (148.4 + 32.3i)$ |
| $10^6 c_6^{eff}$ | $633.8 - 38.6i (-692.0 - 138.3i) - 649.6 - 94.7i (-642.6 - 96.8i)$ |

III. NUMERICAL RESULTS AND DISCUSSIONS

In the numerical analysis, the CKM matrix elements in the Wolfenstein parameterization read

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

with $(\lambda, A, \rho, \eta) = (0.225, 0.826, 0.159 \pm 0.010, 0.348 \pm 0.010)$. From Refs. [18, 20], we adopt $D(x)$ as

$$D(x) = D_0(x) + \frac{\alpha_s}{4\pi} D_1(x),$$
$$D_0(x) = \frac{x}{8} \left[ -\frac{2 + x}{1 - x} + \frac{3x - 6}{(1 - x)^2} \ln(x) \right],$$
$$D_1(x) = -\frac{23x + 5x^2 - 4x^3}{3(1 - x)^2} + \frac{x - 14x^2 + x^3 + x^4}{(1 - x)^3} \ln(x) + \frac{8x + 4x^2 + x^3 - x^4}{2(1 - x)^3} \ln^2(x) - \frac{4x - x^2}{(1 - x)^2} L_2(1 - x) + 8x \frac{\partial D_0(x)}{\partial x} \ln(\mu^2/m_W^2),$$

where $L_2(1 - x) \equiv \int_x^1 \ln(t)/(1 - t)dt$ and $\mu = m_b$. For $B \to p\bar{p}M_{(c)}$, we present $c_i^{eff}$ in Table II, where $b$ and $\bar{b}$ decays are both considered, together with the decay constants $(f_\pi, f_K, f_\rho, f_{K^*}) = (130.2 \pm 1.2, 155.7 \pm 0.3, 210.6 \pm 0.4, 204.7 \pm 6.1) \text{ MeV}$ [7, 33] and $(f_D, f_{D^*}) = (208.9 \pm 6.5, 252.2 \pm 22.7) \text{ MeV}$ [22, 34]. In the generalized edition of the factorization [24, 31], $N_c$ is taken as the effective color number with $N_c^{(eff)} = (2, 3, \infty)$, in order that the non-factorizable QCD corrections can be estimated. We perform the minimum $\chi^2$-fit of

$$\chi^2 = \sum \left( \frac{O_{th} - O_{ex}}{\sigma_{ex}^i} \right)^2 + \left( \frac{|V_{ub}|_{th} - |V_{ub}|_{ex}}{\sigma_{|V_{ub}|_{ex}}} \right)^2,$$

in order to test if the observables for $B \to B\bar{B}M_{(c)}$ and $B \to B\bar{B}L\bar{L}'$ can be both accommodated, where $O_{th}^i$ stand for the theoretical calculations of $B$, $A_{CP}$ and $A_{FB}$, while $O_{ex}^i$ the experimental inputs in Table III together with $\sigma_{ex}^i$ the experimental errors. Since the
TABLE II. Experimental data for the $B^- \rightarrow p\bar{p}\ell^-\nu_\ell$ and $B \rightarrow p\bar{p}M_{(c)}$ decays, where the notation $\dagger$ for $A_{FB}$ denotes the contribution from $m_{p\bar{p}} < 2.85$ GeV, and $B(B^- \rightarrow p\bar{p}\mu^-\nu_\mu)$ has combined the Belle and LHCb data in Eq. (11).

| Decaying modes | Data          |
|----------------|--------------|
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}\ell^-\nu_\ell)$ | $8.2 \pm 3.8$ [14] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}\mu^-\nu_\mu)$ | $5.2 \pm 0.4$ [14, 15] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}\pi^-)$ | $5.9 \pm 0.5$ [7] |
| $10^6 \mathcal{B}(B^0 \rightarrow p\bar{p}K^-)$ | $2.66 \pm 0.32$ [7] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}\pi^-)_{ex}$ | $0 \pm 4$ [7] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}K^-)_{ex}$ | $0 \pm 4$ [7] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}\pi^-)_{332}$ | $(-40.9 \pm 3.4) \dagger$ [34] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}K^-)_{332}$ | $(49.5 \pm 1.4) \dagger$ [34] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}\pi^-)$ | $4.6 \pm 1.3$ [7] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}K^-)$ | $3.4 \pm 0.8$ [39] |
| $10^6 \mathcal{B}(B^0 \rightarrow p\bar{p}K^{*0})$ | $1.2 \pm 0.3$ [39] |
| $10^6 \mathcal{B}(B^- \rightarrow p\bar{p}K^{*0})$ | $21 \pm 11$ [7] |
| $10^6 \mathcal{B}(B^0 \rightarrow p\bar{p}D^{0\ast})$ | $1.04 \pm 0.07$ [7] |
| $10^6 \mathcal{B}(B^0 \rightarrow p\bar{p}D^{\ast\ast})$ | $0.99 \pm 0.11$ [7] |

$|V_{ub}|$ in Eq. (2) is for the exclusive baryonic $B_{(s)}$ decays, which can be different from that in the inclusive ones [35–37], we choose $|V_{ub}|_{ex} = (3.43 \pm 0.32) \times 10^{-3}$ determined from the $\bar{B}_s^0$ and baryonic $\Lambda_b$ decays [7] as our experimental input in Eq. (15).

Subsequently, we obtain $\chi^2/n.d.f = 1.86$ as a measure of the global fit, where $n.d.f = 5$ denotes the number of degrees of freedom. For $F_{BB'}$, we extract that

$$(D_1, D_2) = (11.2 \pm 43.5, 332.3 \pm 17.2) \text{ GeV}^5,$$

$$(D_3^2, D_4^3, D_5^4) = (47.7 \pm 10.1, 442.2 \pm 103.4, -38.7 \pm 9.6, 80.7 \pm 27.2) \text{ GeV}^4,$$

$$(\tilde{D}_1, \tilde{D}_2, \tilde{D}_3^2) = (-59.9 \pm 12.9, 23.8 \pm 6.8, 90.9 \pm 11.1, 131.7 \pm 330.7) \text{ GeV}^4,$$

with $N_{cD}^{eff} = 2$ and $\infty$ for $B \rightarrow p\bar{p}M$ and $B \rightarrow p\bar{p}M_c$, respectively. Using the parameters in Eq. (16), we draw the $p\bar{p}$ invariant mass spectrum for $B^- \rightarrow p\bar{p}\ell^-\nu_\ell$ in Fig. 3. We are enabled to calculate the branching fractions and angular asymmetries of $B^- \rightarrow p\bar{p}\ell^-\nu_\ell, \Lambda\bar{p}\nu\bar{\nu}$ and $\bar{B}_s^0 \rightarrow p\Lambda\ell^-\nu_\ell, \Lambda\Lambda\nu\bar{\nu}$, of which the results are compared with the experimental data in Table 11

IV. DISCUSSIONS AND CONCLUSIONS

Since $\chi^2/n.d.f = 1.86$ presents a reasonable fit, $F_{BB'}$ extracted in this work can be the universal form factors for the hadronic and semileptonic decay channels. By contrast, $F_{BB'}$ for the previous studies of $B^- \rightarrow p\bar{p}\ell^-\nu_\ell$ and $B^- \rightarrow \Lambda\bar{p}\nu\bar{\nu}$ come from the global fit that has
FIG. 3. The $p\bar{p}$ invariant mass spectrum of $B^− \to p\bar{p}\mu^−\bar{\nu}_\mu$, where the data points are from LHCb [15].

not included $\mathcal{B}(B^− \to p\bar{p}e^−\bar{\nu}_e)$, $\mathcal{B}(\bar{B}^0 \to p\bar{p}D^{*0})$, $\mathcal{B}(B \to p\bar{p}K)$, $A_{FB}(B^− \to p\bar{p}K^−)$, and $\mathcal{B}(B^− \to p\bar{p}p^−\bar{\nu}_e)$). Using the new determination, it is demonstrated that $\mathcal{B}(B^− \to p\bar{p}\mu^−\bar{\nu}_\mu) = (5.3 \pm 2.0) \times 10^{-6}$, $\mathcal{B}(B^− \to p\bar{p}\mu^−\bar{\nu}_\mu) = (5.4 \pm 2.0) \times 10^{-6}$, and the partial branching fraction of $B^− \to p\bar{p}\mu^−\bar{\nu}_\mu$ as a function of $m_{p\bar{p}}$ in Fig. 3 are all in agreement with the current data.

Moreover, we obtain $\mathcal{B}(B^− \to \Lambda\bar{\nu}\bar{\nu}) = (3.5 \pm 1.0) \times 10^{-8}$ nearly 20 times smaller than that in Ref. [9].

The decay channel $\bar{B}_s^0 \to \Lambda\bar{p}K^+(\bar{\Lambda}pK^-)$ is the first observation of a baryonic $\bar{B}_s^0$ decay [40], whose branching fraction $\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{p}K^+ + \bar{\Lambda}pK^-) = 5.46 \times 10^{-6}$ is shown to be as TABLE III. Our calculations for the semileptonic $B \to \bar{B}_sL\bar{L}'$ decays. For $\mathcal{B}(B \to \bar{B}^0\nu\bar{\nu})$, the values in the parentheses correspond to $\ell = (e, \mu, \tau)$, where the first and second errors come from $|V_{ub}|$ and the form factors in Eq. [10], respectively. For $\mathcal{B}(B \to \bar{B}^0\nu\bar{\nu}) = \Sigma_\ell\mathcal{B}(B \to \bar{B}^0\nu\ell\bar{\nu}_\ell)$ and $A_{FB}(B \to \bar{B}^0\nu\bar{\nu})$, the errors take into account the uncertainties of the form factors in Eq. [16].
large as those of the three-body baryonic $B^-$ ($B^0$) decays. We hence infer that there should be a semileptonic baryonic $B^0_s$ decay compatible with $B^- \rightarrow p\bar{p}\ell\bar{\nu}_\ell$. In our prediction, we present

$$B(B^0_s \rightarrow p\bar{\Lambda}e^-\bar{\nu}_e, p\bar{\Lambda}\mu^-\bar{\nu}_\mu) = (2.1 \pm 0.6, 2.1 \pm 0.6) \times 10^{-6},$$
$$B(\bar{B}^0_s \rightarrow p\bar{\Lambda}\tau^-\bar{\nu}_\tau) = (1.7 \pm 1.0) \times 10^{-6},$$

accessible to the LHCb experiment, along with $B(B^0_s \rightarrow \Lambda\bar{\nu}\nu) = (0.8 \pm 0.2) \times 10^{-8}$. We study the angular asymmetries of the semileptonic $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'LL'$ decays, where $A_{FB,\theta_B}(B^- \rightarrow p\bar{p}\ell^-\bar{\nu}_\ell)$ are around several percents, whereas $A_{FB,\theta_B}(B^0_s \rightarrow p\bar{\Lambda}e^-\bar{\nu}_e, p\bar{\Lambda}\mu^-\bar{\nu}_\mu)$ and $A_{FB,\theta_B}(\bar{B}^0_s \rightarrow \Lambda\bar{\nu}\nu)$ can be around 25%. This implies a theoretical sensitivity for $F_{\mathbf{B}\bar{\mathbf{B}}'}$ to be confirmed by future measurements, as those of the three-body baryonic $B$ decays [3, 22, 32].

In summary, we have investigated the semileptonic $B^-(\bar{B}^0_s) \rightarrow \mathbf{B}\bar{\mathbf{B}}'LL'$ decays with $LL' = (\ell\bar{\nu}_\ell, \nu\bar{\nu})$, which depend on the $B \rightarrow \mathbf{B}\bar{\mathbf{B}}'$ transition form factors newly determined from the global fit that includes the data of the $B \rightarrow p\bar{p}M_{(c)}$ and $B \rightarrow p\bar{p}e^-\bar{\nu}_e, p\bar{p}\mu^-\bar{\nu}_\mu$ decays. In our demonstration, $B(B^- \rightarrow p\bar{p}e^-\bar{\nu}_e, p\bar{p}\mu^-\bar{\nu}_\mu)$ once overestimated to be as large as $10^{-4}$ has been reduced to be around $5 \times 10^{-6}$, in agreement with the current data. We have also presented $B(B^- \rightarrow \Lambda\bar{\nu}\nu) = (3.5 \pm 1.0) \times 10^{-8}$ accessible to the LHCb experiment. It has been found that $B(B^0_s \rightarrow p\bar{\Lambda}e^-\bar{\nu}_e, p\bar{\Lambda}\mu^-\bar{\nu}_\mu) = (2.1 \pm 0.6, 2.1 \pm 0.6) \times 10^{-6}$ and $B(\bar{B}^0_s \rightarrow p\bar{\Lambda}e^-\bar{\nu}_e) = (1.7 \pm 1.0) \times 10^{-6}$ can be compatible with $B(B^- \rightarrow p\bar{p}\ell^-\bar{\nu}_\ell)$, such that promising for future measurements.

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