Large CP violation
in internal $W$-emission dominated baryonic $B$ decays

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(Dated: September 20, 2019)

Abstract

The observation of CP violation has been experimentally verified in numerous $B$ decays but is yet to be confirmed in final states with half-spin particles. We focus our attention on baryonic $B$-meson decays mediated dominantly through internal $W$-emission processes and show them to be promising processes to observe for the first time CP violating effects in $B$ decays to final states with half-spin particles. Specifically, we study the branching fractions and direct CP violating asymmetries of the baryonic $B$ meson decays $\bar{B}^0 \to p\bar{p}M^{(*)0}$, where $M^{(*)0}$ stands for $\pi^0(\rho^0)$. We predict the latter to be large. We calculate that $\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0) = (5.5 \pm 1.0) \times 10^{-7}$, in agreement with current data, together with $\mathcal{B}(\bar{B}^0 \to p\bar{p}\rho^0) \simeq \mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0)/3$, and $A_{CP}(\bar{B}^0 \to p\bar{p}\pi^0, p\bar{p}\rho^0, p\bar{p}\pi^+\pi^-) = (-16.0 \pm 2.3, -12.2 \pm 2.1, -11.5 \pm 1.8)\%$. With measured branching fractions $\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0, p\bar{p}\rho^0, p\bar{p}\pi^+\pi^-) \sim \mathcal{O}(10^{-6})$, we point out that $A_{CP} \sim -(10 - 20)\%$ can be new observables for CP violation, accessible to the Belle II and/or LHCb experiments.

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I. INTRODUCTION

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

Baryonic $B$ decays can be an important stage to investigate CPV within the SM and beyond. With $M^{(*)}$ denoting a pseudoscalar (vector) meson such as $K^{(*)}, \pi, \rho, D^{(*)}$, the $B \to p\bar{p}M^{(*)}$ decays have been carefully studied by the B factories and the LHCb experiment [4–10]. Experimental information includes measurements of branching fractions, angular distribution asymmetries, polarizations of vector mesons in $B \to p\bar{p}K^*$, Dalitz plot information, and $p\bar{p}$ ($M^{(*)}p$) invariant mass spectra. This helps to improve the theoretical understanding for the di-baryon production in $B \to BB'$ [11–15], such that the data can be well interpreted. Predictions are confirmed by recent measurements. For example, one obtains $\mathcal{B}(\bar{B}_s^0 \to p\bar{p}\Lambda K^- + \Lambda \bar{p}K^+) = (5.1 \pm 1.1) \times 10^{-6}$ [16], in excellent agreement with the values of $(5.46 \pm 0.61 \pm 0.57 \pm 0.50 \pm 0.32) \times 10^{-6}$ measured by LHCb [17], and the theoretical extension to four-body decays allows to interpret the branching fraction measurement of $\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-)$ [18, 20]. The same can be said for CP asymmetries. Indeed, $\mathcal{A}_{CP}(B^- \to p\bar{p}M^{(*)}-)$, where $M^{(*)-} = (K^{*-}, K^-, \pi^-)$, have been predicted as $(22, 6, -6)\%$ [21, 22], in comparison with the experimental values of $(21 \pm 16, 2.1 \pm 2.0 \pm 0.4, -4.1 \pm 3.9 \pm 0.5)\%$ [1, 4].

In this letter, we focus our attention on baryonic $B$-meson decays mediated dominantly through internal $W$-emission processes and show them to be promising processes to observe for the first time CP violating effects in $B$ decays to final states with half-spin particles. Specifically, we will study the branching fractions and direct CP violating asymmetries of the decays $\bar{B}^0 \to p\bar{p}\pi^0(\rho^0), p\bar{p}\pi^+\pi^-$. Their measured branching fractions are not small, given by [18, 23]

$$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0) = (5.0 \pm 1.8 \pm 0.6) \times 10^{-7},$$

$$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-) = (2.7 \pm 0.1 \pm 0.1 \pm 0.2) \times 10^{-6};$$  \hspace{1cm} (1)
which makes possible observation for CPA. We will predict the CP violating asymmetries to be large.

II. FORMALISM

As seen in Fig. 1, the $\bar{B}^0 \to p\bar{p}M^{(*)0}$ decays, with $M^{(*)0}$ standing for $\pi^0(\rho^0)$, proceed through two different configurations; with $M^0$ replaced by $\pi^+\pi^-$, $\bar{B}^0 \to p\bar{p}\pi^+\pi^-$ has similar configurations. In terms of the effective Hamiltonian [24], the decay amplitudes of $\bar{B}^0 \to p\bar{p}X_M$, with $X_M \equiv (M^{(*)0}, \pi^+\pi^-)$, can be written as [15, 16, 19]

$$A(\bar{B}^0 \to p\bar{p}X_M) = A_1(X_M) + A_2(X_M),$$

(2)

where $A_{1,2}(M_X)$ correspond to Fig. II(a,b,c) and (d,e,f), respectively. Explicitly, $A_{1,2}$ are given by [13, 15, 16, 25, 27]

$$A_1(X_M) = \frac{G_F}{\sqrt{2}} \left[ \left\langle \langle p\bar{p} | u^\mu (\alpha_2^+ - \alpha_2^- \gamma_5) u | 0 \rangle + \langle p\bar{p} | d^\mu (\alpha_3^+ - \alpha_3^- \gamma_5) d | 0 \rangle \right]\times \langle X_M | d\gamma^\mu (1 - \gamma_5)b|\bar{B}^0 \rangle + \alpha_6 \langle p\bar{p} | \bar{d}(1 + \gamma_5)d|0 \rangle \langle X_M | \bar{d}(1 - \gamma_5)b|\bar{B}^0 \rangle \right],$$

$$A_2(X_M) = \frac{G_F}{\sqrt{2}} \left[ \left\langle \langle X_M | u^\mu (\alpha_2^+ - \alpha_2^- \gamma_5) u | 0 \rangle + \langle X_M | d^\mu (\alpha_3^+ - \alpha_3^- \gamma_5) d | 0 \rangle \right] \right].$$

3
\[ \times \langle pp|\bar{d}\gamma_\mu(1-\gamma_5)b|\bar{B}^0\rangle + \alpha_6\langle X_M|\bar{d}(1+\gamma_5)d|0\rangle \langle pp|\bar{d}(1-\gamma_5)b|\bar{B}^0\rangle \} , \]  

(3)

with \( G_F \) the Fermi constant. The parameters \( \alpha_i \) are defined as

\[
\begin{align*}
\alpha_2^\pm &= V_{ub}V^*_{ud}a_2 - V_{tb}V^*_{td}(a_3 \pm a_5 \pm a_7 + a_9), \\
\alpha_3^\pm &= -V_{ub}V^*_{td}(a_3 + a_4 \pm a_7 - a_9 - a_{10}/2), \\
\alpha_6 &= V_{tb}V^*_{td}(2a_6 - a_8),
\end{align*}
\]

(4)

where \( V_{ij} \) are the CKM matrix elements, and \( a_i \equiv c_i^{eff} + c_i^{eff}/N_c \) for \( i = \text{odd (even)} \) consist of the effective Wilson coefficients \( c_i^{eff} \) and the color number \( N_c \) [25]. We note that \( A_1(\pi^+\pi^-) \gg A_2(\pi^+\pi^-) \) [19].

The \( B \to X_M \) transition matrix elements in \( A_1(X_M) \) are written as [28, 29]

\[
\begin{align*}
\langle M|\bar{q}\gamma_\mu|B\rangle &= \left( p_B + p \right)\mu - \frac{m_B^2 - m_M^2}{t}q^\mu F_{BM}^0(t) + \frac{m_B^2 - m_M^2}{t}q^\mu F_{BM}^0(t), \\
\langle M^*|\bar{q}\gamma_\mu|B\rangle &= \varepsilon_{\mu\nu\alpha\beta} \bar{p}_B^\nu \varepsilon_{\mu}^\alpha \zeta_{BM}^\beta \frac{2V_1(t)}{m_B + m_M}, \\
\langle M^*|q\gamma_5\gamma_\mu|B\rangle &= i \left[ \varepsilon_\mu^\ast \cdot q \left( m_B + m_M \right) A_1(t) + i \varepsilon_\mu^\ast \cdot q \left( 2m_M \right) A_0(t) \right. \\
&\quad - \left. i \left( p_B + p \right)\mu - \frac{m_B^2 - m_M^2}{t}q_\mu \right] \varepsilon^\ast \cdot q \frac{A_2(t)}{m_B + m_M}, \\
\langle M_1M_2|\bar{q}\gamma_\mu(1-\gamma_5)b|B\rangle &= h \varepsilon_{\mu\alpha\beta}\bar{p}_B^\nu (p_{M_2} + p_{M_1})^\alpha (p_{M_2} - p_{M_1})^\beta \\
&\quad + i r q_\mu + i w_+ (p_{M_2} + p_{M_1})\mu + i w_- (p_{M_2} - p_{M_1}),
\end{align*}
\]

(5)

with \( p_\mu (\varepsilon_\mu^\ast) \) the four-vector (polarization) of \( M^{(*)} \), \( t \equiv q^2 \) and \( q = p_B + p_{B'} \) as the momentum transfer, where \( F_{BM}^{0,1} \), \( (V_1, A_{0,1,2}) \) and \( (h, r, w_{\pm}) \) are the \( B \to M, M^* \) and \( M_1M_2 \) transition form factors, respectively. The matrix elements of the \( B \to \bar{B}B' \) transitions are expressed as [27]

\[
\begin{align*}
\langle \bar{B}B'|\bar{q}\gamma_\mu q'|0\rangle &= \bar{u} \left[ F_1 \gamma_\mu + \frac{F_2}{m_B + m_{B'}} i \sigma_\mu q_\mu \right] v, \\
\langle \bar{B}B'|\bar{q}\gamma_\mu\gamma_5 q'|0\rangle &= \bar{u} \left[ g_A \gamma_\mu + \frac{h_A}{m_B + m_{B'}} q_\mu \right] \gamma_5 v, \\
\langle \bar{B}B'|qq'|0\rangle &= f_S \bar{u}v, \quad \langle \bar{B}B'|q\gamma_5 q'|0\rangle = g_P \bar{u} \gamma_5 v,
\end{align*}
\]

(6)

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

For \( A_2(\bar{B}^0 \to ppM^{(*)0}) \), the \( 0 \to M^{(*)} \) matrix elements are written as [1]

\[
\begin{align*}
\langle M|\bar{q}\gamma_\mu\gamma_5 q'|0\rangle &= -i f_M p_\mu, \quad \langle M^*|\bar{q}\gamma_\mu q'|0\rangle = m_M f_M^* \varepsilon_\mu^\ast,
\end{align*}
\]

(7)
with $f_{M^{(*)}}$ the decay constant. Those of the $B \to B\bar{B}'$ transitions are given by

\[ (B\bar{B}' | q\gamma_\mu | B) = i\bar{u} [g_1 \gamma_\mu + g_2 i\sigma_{\mu\nu} p^\nu + g_3 p_\mu + g_4 q_\mu + g_5 (p_{\bar{B}} - p_B)_\mu] \gamma_5 v, \]

\[ (B\bar{B}' | q\gamma_\mu \gamma_5 | B) = i\bar{u} [f_1 \gamma_\mu + f_2 i\sigma_{\mu\nu} p^\nu + f_3 p_\mu + f_4 q_\mu + f_5 (p_{\bar{B}} - p_B)_\mu] \gamma_5 v, \]

\[ (B\bar{B}' | \bar{q} \gamma_\mu | B) = i\bar{u} [\bar{g}_1 \gamma_\mu + \bar{g}_2 (E_{\bar{B}} + E_B) + \bar{g}_3 (E_{\bar{B}} - E_B)] \gamma_5 v, \]

\[ (B\bar{B}' | \bar{q} \gamma_5 | B) = i\bar{u} [\bar{f}_1 \gamma_\mu + \bar{f}_2 (E_{\bar{B}} + E_B) + \bar{f}_3 (E_{\bar{B}} - E_B)] \gamma_5 v, \]

where $g_i(f_i) (i = 1, 2, ..., 5)$ and $\bar{g}_j(\bar{f}_j) (j = 1, 2, 3)$ are the $B \to B\bar{B}'$ transition form factors.

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

\[ F_A(t) = \frac{F_A(0)}{(1 - \frac{t}{M_A^2})(1 - \frac{t}{M_A^2} + \frac{\alpha_1^2}{M_A^2})}, \quad F_B(t) = \frac{F_B(0)}{1 - \frac{\alpha_1^2}{M_B^2} + \frac{\alpha_1^2}{M_B^2}}, \]

where $F_A = (F_{1BM}, V_1, A_0)$ and $F_B = (F_{0BM}^*, A_{1,2})$. The approach of perturbative QCD counting rules derives the baryonic form factors and $B \to M_1 M_2$ ones with $1/t^n$ as the leading-order expansion

\[ F_1 = \frac{C_{F_1}}{t^2}, \quad g_A = \frac{C_{gA}}{t^2}, \quad f_S = \frac{C_{fS}}{t^2}, \quad g_P = \frac{C_{gP}}{t^2}, \]

\[ f_i = \frac{D_{f_i}}{t^2}, \quad g_i = \frac{D_{g_i}}{t^2}, \quad \bar{f}_i = \frac{D_{\bar{f}_i}}{t^2}, \quad \bar{g}_i = \frac{D_{\bar{g}_i}}{t^2}, \]

\[ h = \frac{C_h}{t^2}, \quad w = \frac{D_w}{t^2}, \]

where $C_i = C_i[\ln(t/\Lambda^2_0)]^{-\gamma}$ with $\gamma = 2.148$ and $\Lambda_0 = 0.3$ GeV. In Ref. [35], $F_2 = F_1/(\ln[t/\Lambda^2_0])$ is calculated to be much less than $F_1$, hence we neglect it. Since $h_A$ is regarded to cause $B(\bar{B}^0 \to p\bar{p}) \sim 10^{-8}$ [36, 37, 38], we neglect $h_A$ also. The neglecting of $(r, w_\perp)$ in Eq. [15] is by following Refs. [33, 34], which is due to the fact that their parity quantum numbers disagree with the experimental evidence of $J^P = 1^-$ for the meson-pair production [40].

The constants $C_i$ ($D_i$) can be decomposed as another sets of parameters that obey the $SU(3)$ flavor and $SU(2)$ spin symmetries, derived in Refs. [19, 27, 31] and [12, 13, 16, 21, 26], respectively. Explicitly, they are given by

\[ (C_{F_1}, C_{gA}) = \frac{1}{3}(5C_{11} + C_{77} + 5C_{11}^* - C_{88}^*), \quad (\langle \bar{p}\bar{p}|(\bar{u}u)_{V,A}|0\rangle) \]

\[ (C_{F_1}, C_{gA}, C_{fS}, C_{gP}) = \frac{1}{3}(C_1 + 2C_7 C_{11}^* - 2C_{88}^* C_1, C_7, C_8^*), \quad (\langle \bar{p}\bar{p}|(\bar{d}d)_{V,A,S,P}|0\rangle) \]

\[ (D_{g_i}, D_{g_i}, D_{f_i}) = \frac{1}{3}(D_{11} \mp 2D_{77}, -D_{77}, D_{77}^*), \quad (\langle \bar{p}\bar{p}|(\bar{d}d)_{V,A}|\bar{B}^0\rangle) \]

\[ (D_{g_i}, D_{g_{2,3}}, D_{f_{2,3}}) = \frac{1}{3}(D_{11} \mp 2D_{77}, -D_{77}^{2,3}, -D^{2,3}_7), \quad (\langle \bar{p}\bar{p}|(\bar{d}d)_{S,P}|\bar{B}^0\rangle) \]
with \( j = 2, \ldots, 4, 5 \), where \( \delta C_{||(||)} (\delta \bar{C}_{||}) \) in \( C^*_C = C_{||(||)} + \delta C_{||(||)} \) \( (\bar{C}^*_{||} = \bar{C}_{||} + \delta \bar{C}_{||}) \) is to account for the broken effects, used to explain the large angular distribution asymmetries in \( B \to \Lambda \bar{p}\pi \) \([38]\). The direct CP violating asymmetry is defined as

\[
\mathcal{A}_{CP}(B \to \bar{B}B'X_M) = \frac{\Gamma(B \to \bar{B}B'X_M) - \Gamma(\bar{B} \to \bar{B}B'X_M)}{\Gamma(B \to \bar{B}B'X_M) + \Gamma(\bar{B} \to \bar{B}B'X_M)}
\]

after integration over the phase-space in the three- and four-body decays \([1, 15]\), where \( \bar{B} \to \bar{B}B'X_M \) denotes the antiparticle decay.

TABLE I. The \( \bar{B}^0 \to M^{(*)}0 \) transition form factors at zero-momentum transfer, with \( (M_A, M_B) = (5.32, 5.32) \) and \( (5.27, 5.32) \) GeV for \( \pi \) and \( \rho \), respectively.

| \( \bar{B}^0 \to \pi^0, \rho^0 \) | \( F_{1,0}^{B\pi} \) | \( F_{0}^{B\pi} \) | \( V_1 \) | \( A_0 \) | \( A_1 \) | \( A_2 \) |
|-----------------|----------------|----------------|--------|--------|--------|--------|
| \( \sqrt{2}f(0) \) | 0.29 | 0.29 | 0.31 | 0.30 | 0.26 | 0.24 |
| \( \sigma_1 \) | 0.48 | 0.76 | 0.59 | 0.54 | 0.73 | 1.40 |
| \( \sigma_2 \) | — | 0.28 | — | — | 0.10 | 0.50 |

III. NUMERICAL ANALYSIS

The numerical analysis relies on the following. The CKM matrix elements are calculated via the Wolfenstein parameterization \([1]\), with the world-average values

\[
\lambda = 0.22453 \pm 0.00044 , A = 0.836 \pm 0.015 , \bar{\rho} = 0.122_{-0.017}^{+0.018} , \bar{\eta} = 0.355_{-0.011}^{+0.012} . \tag{13}
\]

The decay constants are \( f_{\pi,\rho} = (130.4 \pm 0.2, 210.6 \pm 0.4) \) MeV \([1]\), with \( (f^{(\pi,\rho)} = (f_{\pi}, f_{\rho})/\sqrt{2} \). We adopt the \( B \to M^{(*)} \) transition form factors in Ref. \([30]\), listed in Table II.

The \( C_{h,w} \) for \( B^0 \to \pi^+\pi^- \) and \( C_i(D_i) \) for \( 0 \to p\bar{p} \) \( (B^0 \to p\bar{p}) \) have been determined as \([13, 16, 19]\)

\[
(C_h, C_{w-}) = (3.6 \pm 0.3, 0.7 \pm 0.2) \text{ GeV}^3 ,
\]

\[
(C_{||}, C_{||}, \bar{C}_{||}) = (154.4 \pm 12.1, 18.1 \pm 72.2, 537.6 \pm 28.7) \text{ GeV}^4 ,
\]

\[
(\delta C_{||}, \delta C_{||}, \delta \bar{C}_{||}) = (19.3 \pm 21.6, -477.4 \pm 99.0, -342.3 \pm 61.4) \text{ GeV}^4 ,
\]

\[
(D_{||}, D_{||}) = (45.7 \pm 33.8, -298.2 \pm 34.0) \text{ GeV}^5 ,
\]

\[
(D_{||}^2, D_{||}^4, D_{||}^2) = (33.1 \pm 30.7, -203.6 \pm 133.4, 6.5 \pm 18.1, -147.1 \pm 29.3) \text{ GeV}^4 ,
\]

\[
(D_{||}, D_{||}^2, D_{||}^3) = (35.2 \pm 4.8, -38.2 \pm 7.5, -22.3 \pm 10.2, 504.5 \pm 32.4) \text{ GeV}^4 . \tag{14}
\]
For $\alpha_i$ in Eq. (4), the effective Wilson coefficients $c^\text{eff}_i$ are calculated at the $m_b$ scale in the NDR scheme, see Ref. [25]. They are related to the size of the decay, where the strong phases, together with the weak phase in $V_{ub}$ and $V_{td}$, play the key role in $A_{CP}$.

IV. DISCUSSIONS AND CONCLUSIONS

Our results for the branching fractions and CP violating asymmetries of $\bar{B}^0 \to p\bar{p}X_M$ decays are summarized in Table II, where we have used $N_c = 2$, leading to $a_2 \simeq 0.22$, and averaged the particle and antiparticle contributions for the total branching fractions.

In the generalized factorization approach, $N_c$ is taken as a floating number in order to take into account the non-factorizable effects [25]. Factorization is regarded to be valid provided that the data can be explained with $N_c$ in the range between 2 and $\infty$, which is in accordance with $a_2 \sim \mathcal{O}(0.2 - 0.3)$, commonly used in the study of internal $W$-emission $b$-hadron decays [41–45]. Indeed, with $a_2 \simeq 0.22$, where $N_c = 2$, we have interpreted $B(\bar{B}^0 \to p\bar{p}\pi^0, p\bar{p}\pi^+\pi^-)$. The highly accurate experimental measurement of the branching fraction of $\bar{B}^0 \to p\bar{p}\rho^0$ is crucial here.

The $\bar{B}^0 \to p\bar{p}\pi^0(\rho^0)$ branching fraction, which comes from the constructive interference of two amplitudes, $A_{1,2}$, can be seen as the result of partial branching fractions $B_1(\bar{B}^0 \to p\bar{p}\pi^0)$ and $B_2(\bar{B}^0 \to p\bar{p}\rho^0)$, together with the interference term $B_{12}^I$, namely $B(\bar{B}^0 \to p\bar{p}\pi^0) = B_1 + B_2 + B_{12}$, with $(B_1, B_2, B_{12}) = (4.2, 0.4, 0.9) \times 10^{-7}$. The $\bar{B}^0 \to p\bar{p}\rho^0$ branching fraction is calculated as

| TABLE II. Decay branching fractions and direct CP asymmetries of $\bar{B}^0 \to p\bar{p}X_M$, where the first errors come from the uncertainties of the CKM matrix elements, and the second ones from those of the decay constants and form factors. |
|---|---|---|
| $10^7 B(\bar{B}^0 \to p\bar{p}\pi^0)$ | our result | data |
| $10^7 B(\bar{B}^0 \to p\bar{p}\rho^0)$ | $1.9 \pm 0.1 \pm 0.4$ | — |
| $10^6 B(\bar{B}^0 \to p\bar{p}\pi^+\pi^-)$ | $2.7 \pm 0.2 \pm 0.7$ | $2.7 \pm 0.2$ [18] |
| $A_{CP}(\bar{B}^0 \to p\bar{p}\pi^0)$ | $(-16.0 \pm 1.6 \pm 1.7)\%$ | — |
| $A_{CP}(\bar{B}^0 \to p\bar{p}\rho^0)$ | $(-12.2 \pm 1.2 \pm 1.7)\%$ | — |
| $A_{CP}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-)$ | $(11.5 \pm 1.2 \pm 1.4)\%$ | — |
$\mathcal{B}(B^0 \to p\bar{p}\pi^0)/3$, with $(B_1', B_2', B_{1,2}^0) = (2.24, 0.04, -0.38) \times 10^{-7}$.

In $b$-hadron decays the CP asymmetry can be presented as

$$A_{CP} = \frac{2R \sin \delta_W \sin \delta_S}{1 + 2R \cos \delta_W \cos \delta_S + R^2},$$

(15)

where the $\delta_W(S)$ is the weak (strong) phase arising from the tree (penguin)-level contribution of the decay amplitude written as $A = T e^{i\delta_W} + P e^{i\delta_S}$. The ratio $R = P/T$ for tree-dominant decays also plays a key role in $A_{CP}$, apart from $\delta_W$ and $\delta_S$. As the external $W$-emission decay, $B^- \to p\bar{p}\pi^-$ proceeds with $a_1 \sim \mathcal{O}(1.0)$ in the amplitude $[21]$, whereas $\bar{B}^0 \to p\bar{p}\pi^0$ with $a_2$. Hence, $R(\pi^0) > R(\pi^-)$ is in accordance with $a_2 < a_1$, and one should have $|A_{CP}(\bar{B}^0 \to p\bar{p}\pi^0)| > |A_{CP}(B^- \to p\bar{p}\pi^-)|$. In fact, we predict $|A_{CP}(\bar{B}^0 \to p\bar{p}\pi^0)| = (16.0 \pm 2.3)\%$, three times larger than $|A_{CP}(B^- \to p\bar{p}\pi^-)|$ $[21, 22]$.

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

With a predicted large CP asymmetry $A_{CP}(\bar{B}^0 \to p\bar{p}\pi^0) = (-16.0 \pm 2.3)\%$, this decay mode accessible to the Belle II experiment is particularly suited for a potential first observation of CP violation in baryonic $B$ decays in the coming years. The study of the $\bar{B}^0 \to p\bar{p}\pi^+\pi^-$ decay is in the realm of both Belle II and LHCb experiments, both branching fraction of order $10^{-6}$ and predicted direct CP asymmetry $A_{CP} \sim -(10 - 20)\%$ being large.

**ACKNOWLEDGMENTS**

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

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