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# Rates and $CP$ asymmetries of Charmless Two-body Baryonic $B_{u,d,s}$ Decays

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With the experimental evidences of $\overline{B}^0 \to p\bar{p}$ and $B \to \Lambda\bar{p}$ decays, it is now possible to extract both tree and penguin amplitudes of the charmless two-body baryonic $B$ decays for the first time. The extracted penguin-tree ratio agrees with the expectation. Using the topological amplitude approach with the experimental results on $\overline{B}^0 \to p\bar{p}$ and $B \to \Lambda\bar{p}$ decay rates as input, predictions on all other $\overline{B}_q \to \mathscr{B}\overline{\mathscr{B}}$, $\mathscr{B}\overline{\mathscr{D}}$, $\mathscr{D}\overline{\mathscr{B}}$ and $\mathscr{D}\overline{\mathscr{D}}$ decay rates, where $\mathscr{B}$ and $\mathscr{D}$ are the low lying octet and decuplet baryons, respectively, are given. It is non-trivial that the results do not violate any existing experimental upper limit. From the analysis it is understandable that why $\overline{B}^0 \to p\bar{p}$ and $B \to \Lambda\bar{p}$ modes are the first two modes with experimental evidences. Relations on rates are verified using the numerical results. We note that the predicted $B \to p\overline{\Delta^{++}}$ rate is close to the experimental bound, which has not been updated in the last ten years. Direct CP asymmetries of all $\overline{B}_q \to \mathscr{B}\overline{\mathscr{B}}$, $\mathscr{B}\overline{\mathscr{D}}$, $\mathscr{D}\overline{\mathscr{B}}$ and $\mathscr{D}\overline{\mathscr{D}}$ modes are explored. Relations on CP asymmetries are examined using the numerical results. The direct CP asymmetry of $\overline{B}^0 \to p\bar{p}$ decay can be as large as ±50%.

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## 1. Introduction

Recently, LHCb collaboration reported the evidence for the first penguin dominated charmless two-body baryonic mode, $B^- \to \Lambda\bar{p}$ decay, at $4.1\sigma$ level [1], giving

$$\mathscr{B}(B^- \to \Lambda\bar{p}) = (2.4^{+1.0}_{-0.8} \pm 0.3) \times 10^{-7}, \tag{1.1}$$

with the experimental rate of the tree-dominated $\overline{B}^0 \to p\bar{p}$ decay [2],

$$\mathscr{B}(\overline{B}^0 \to p\overline{p}) = (1.47^{+0.62+0.35}_{-0.51-0.14}) \times 10^{-8}, \tag{1.2}$$

it is now possible to extract both tree and penguin amplitudes at the same time.

The two-body baryonic decays are in general non-factorizable, which makes the theoretical study difficult. In general, one has to resort to model calculations. There are pole model, sum rule, model, related studies [3]. Predictions from various models usually differ a lot, and explicit calculations usually give too large rates on the charmless modes. For example, all existing predictions on $\overline{B}^0 \to p\bar{p}$ rate are off by several order of magnitude comparing to the LHCb result [2, 3].

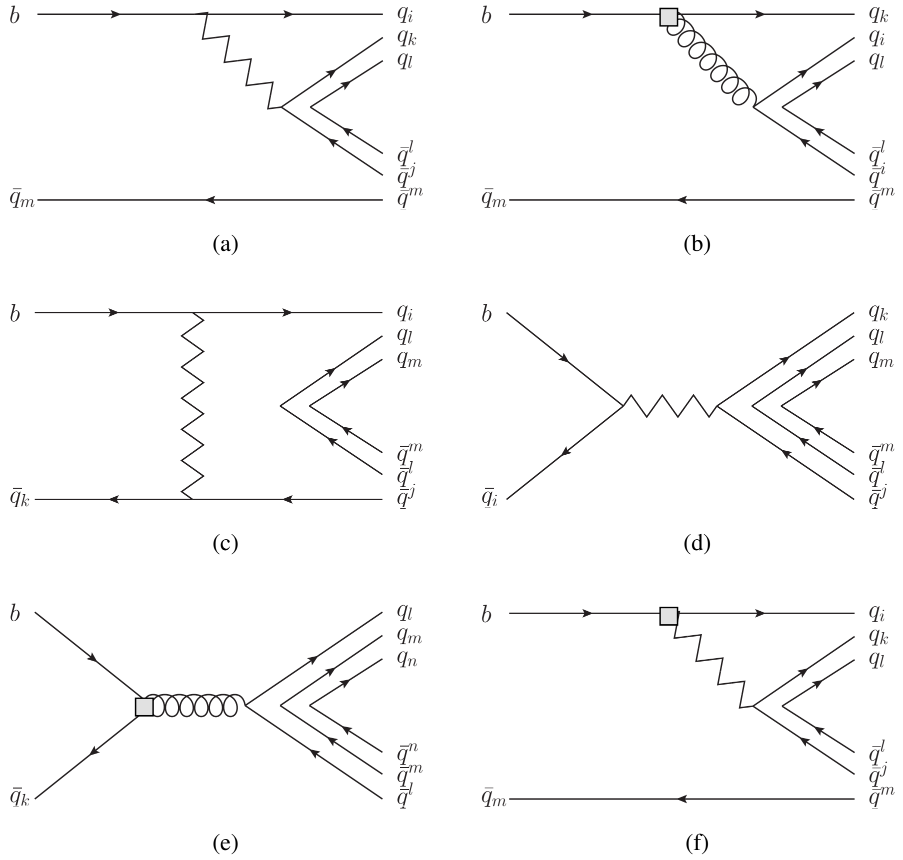
In [4], using the experimental results on the $\overline{B}^0 \to p\bar{p}$ and $B^- \to \Lambda\bar{p}$ decay rates, we extracted both tree and penguin amplitudes for the first time using formalism developed in [5] with the finding in [6] incorporated. Rates and direct $CP$ asymmetries of all low lying charmless two body baryonic decays can be explored. Rates and $CP$ asymmetries of some modes can be checked experimentally in the near future in LHCb and Belle-II. Note that $CP$ asymmetries of some modes can be added to the list of the tests of the Standard Model. In particular, $\Delta S = -1$ pure penguin modes have small $CP$ asymmetries and they are expected to be sensitive to New Physics contributions. These modes are good candidates to be added to the lists of the tests of the Standard Model, especially for those with unsuppressed rates.

## 2. Results on two-body charmless baryonic $B$ decay amplitudes and rates

There are more than 160 $\overline{B} \to \mathscr{D}\overline{\mathscr{D}}$, $\mathscr{D}\overline{\mathscr{B}}$, $\mathscr{B}\overline{\mathscr{D}}$, $\mathscr{B}\overline{\mathscr{B}}$ decay amplitudes [5]. We show a few of them as examples here:

$$\begin{aligned}
A(B^- \to \Lambda\overline{p}) &= \frac{1}{\sqrt{6}}(T'_{1\mathscr{B}\overline{\mathscr{B}}} + 2T'_{3\mathscr{B}\overline{\mathscr{B}}}) + \frac{1}{\sqrt{6}}(10P'_{1\mathscr{B}\overline{\mathscr{B}}} - P'_{2\mathscr{B}\overline{\mathscr{B}}}) - \frac{1}{3\sqrt{6}}(P'_{1EW\mathscr{B}\overline{\mathscr{B}}} - P'_{2EW\mathscr{B}\overline{\mathscr{B}}} \\
&\quad -4P'_{3EW\mathscr{B}\overline{\mathscr{B}}} + 4P'_{4EW\mathscr{B}\overline{\mathscr{B}}}) + \frac{1}{\sqrt{6}}(10A'_{1\mathscr{B}\overline{\mathscr{B}}} - A'_{2\mathscr{B}\overline{\mathscr{B}}}), \\
A(\bar{B}^0 \to p\overline{p}) &= -T_{2\mathscr{B}\overline{\mathscr{B}}} + 2T_{4\mathscr{B}\overline{\mathscr{B}}} + P_{2\mathscr{B}\overline{\mathscr{B}}} + \frac{2}{3}P_{2EW\mathscr{B}\overline{\mathscr{B}}} - 5E_{1\mathscr{B}\overline{\mathscr{B}}} + E_{2\mathscr{B}\overline{\mathscr{B}}} - 9PA_{\mathscr{B}\overline{\mathscr{B}}}, \\
A(\bar{B}^0_s \to p\overline{p}) &= -5E'_{1\mathscr{B}\overline{\mathscr{B}}} + E'_{2\mathscr{B}\overline{\mathscr{B}}} - 9PA'_{\mathscr{B}\overline{\mathscr{B}}}, \\
A(B^- \to p\overline{\Delta^{++}}) &= -\sqrt{6}(T_{1\mathscr{B}\overline{\mathscr{D}}} - 2T_{2\mathscr{B}\overline{\mathscr{D}}}) + \sqrt{6}P_{\mathscr{B}\overline{\mathscr{D}}} + 2\sqrt{\frac{2}{3}}P_{1EW\mathscr{B}\overline{\mathscr{D}}} + \sqrt{6}A_{\mathscr{B}\overline{\mathscr{D}}},
\end{aligned} \tag{2.1}$$

where $T^{(\prime)}$, $P^{(\prime)}$, $E^{(\prime)}$, $A^{(\prime)}$, $PA^{(\prime)}$ and $P^{(\prime)}_{EW}$ are tree, penguin, $W$-exchange, annihilation, penguin annihilation and electroweak penguin amplitudes, respectively, for $\Delta S = 0(-1)$ decays (see Fig. 1). There are some relations on these amplitudes in the large $m_B$ limit [4, 5].



(a) (b)

(c) (d)

(e) (f)

Figure 1: Pictorial representation of (a) $T$ (tree), (b) $P$ (penguin), (c) $E$ ($W$-exchange), (d) $A$ (annihilation), (e) $PA$ (penguin annihilation) and (f) $P_{EW}$ (electroweak penguin) amplitudes in $\overline{B}$ to baryon pair decays. These are flavor flow diagrams.

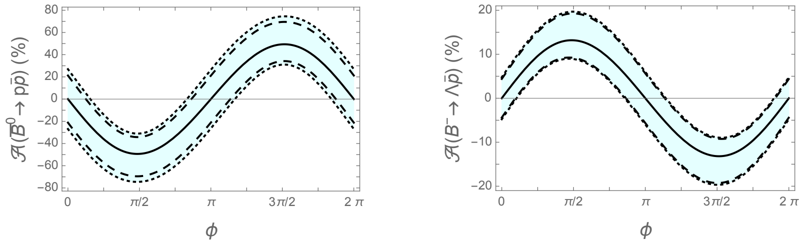
In Table 1 rates of some modes that will cascadely decay to all charged final states and have large decay rates are shown. First of all it is interesting to note that all of the predicted rates satisfy existing data. This is a non-trivial fact as we only make use of $B^0 \to p\bar{p}$ and $B^- \to \Lambda p$ rate. With the experimental evidences of $\overline{B}^0 \to p\overline{p}$ and $B^- \to \Lambda\bar{p}$ decays, it is now possible to extract both tree and penguin amplitudes of charmless two-body baryonic decays for the first time, giving $|P/T| = 0.24 \pm 0.04$, $|T'/P'| = 0.21^{+0.05}_{-0.03}$. The extracted penguin-tree ratio agrees with the expectation. From the results, it is understandable that why $\overline{B}^0 \to p\overline{p}$ and $B^- \to \Lambda\bar{p}$ modes are the first two modes with experimental evidences. There are 23 modes that have relatively sizable rates and can cascadely decay to all charged final states, including $\overline{B}^0 \to p\bar{p}$, $B^- \to \Lambda\bar{p}$, $\Xi^-\overline{\Lambda}$, $\overline{B}{}^0_s \to \Lambda\overline{\Lambda}$, $\Xi^-\overline{\Xi^-}$; $B^- \to p\overline{\Delta^{++}}$, $\overline{B}{}^0_s \to p\overline{\Sigma^{*+}}$, $\overline{B}^0 \to \Xi^-\overline{\Sigma^{*-}}$; $B^- \to \Delta^0\overline{p}$, $\overline{B}{}^0_s \to \Delta^0\overline{\Lambda}$, $\overline{B}^0 \to \Sigma^{*-}\overline{p}$, $\Omega^-\overline{\Xi^-}$, $\Xi^{*0}\overline{\Lambda}$; $\overline{B}^0 \to \Delta^0\overline{\Delta^0}$, $\overline{B}^0 \to \Sigma^{*-}\overline{\Sigma^{*-}}$, $B^- \to \Sigma^{*+}\overline{\Delta^{++}}$, $\Xi^{*0}\overline{\Sigma^{*+}}$, $\Omega^-\overline{\Xi^{*0}}$, $\Sigma^{*-}\overline{\Delta^0}$, $\overline{B}{}^0_s \to \Omega^-\overline{\Omega^-}$, $\Xi^{*0}\overline{\Xi^{*0}}$, $\Sigma^{*+}\overline{\Sigma^{*+}}$ and $\Sigma^{*-}\overline{\Sigma^{*-}}$ decays. In particular, we note that the predicted $B^- \to p\overline{\Delta^{++}}$ rate is close to the experimental bound, which has not been updated in the last ten years [8]. The bounds on $B^- \to \Delta^0\overline{p}$ and $\overline{B}^0 \to \Sigma^{*+}\overline{p}$ rates have not been updated in the last ten years [8, 9] and the bound on $\overline{B}^0 \to \Delta^0\overline{\Delta^0}$ rate has not been updated in about three decades [10], while their rates are predicted

Table 1: Some decay rates of $\Delta S = 0, -1$, $\overline{B}_q \to \mathscr{D}\overline{\mathscr{D}}, \mathscr{B}\overline{\mathscr{D}}, \mathscr{D}\overline{\mathscr{B}}, \mathscr{B}\overline{\mathscr{B}}$ modes. Most of these modes have unsuppressed rates and good detectability, while a few of them are listed as to compare to experimental limits. Note that the $B^0 \to p\bar{p}$ and $B^- \to \Lambda\bar{p}$ rates are taken as inputs of our numerical analysis.

| Mode | $\mathscr{B}(10^{-8})$ | Mode | $\mathscr{B}(10^{-8})$ |
|---|---|---|---|
| $\overline{B}^0 \to p\overline{p}$ | $1.47^{+0.71+0.14+2.07}_{-0.53-0\phantom{.00}-1.16}\pm 0.12$ | $\overline{B}^0 \to \Lambda\overline{\Lambda}$ | $0\pm 0\pm 0^{+0.23+0.0005}_{-0\phantom{.00}-0}$ |
|  | $(1.47^{+0.62+0.35}_{-0.51-0.14})$ [2] |  | $(< 32)$ [7] |
| $B^- \to \Lambda\overline{p}$ | $24.00^{+10.44+2.13+12.48}_{-8.54\phantom{0}-0\phantom{.00}-9.85}\pm 0.02$ | $\overline{B}^0_s \to p\overline{p}$ | $0\pm 0\pm 0^{+0.007}_{-0}$ |
|  | $(24^{+10}_{-8}\pm 3)$ [1] |  | $(2.84^{+2.03+0.85}_{-1.68-0.18})$ [2] |
| $B^- \to \Xi^-\overline{\Lambda}$ | $2.36^{+1.05}_{-0.84}\pm 0^{+2.65}_{-1.67}\pm 0.005$ | $\overline{B}^0_s \to \Xi^-\overline{\Xi^-}$ | $22.63^{+10.02}_{-8.05}\pm 0^{+15.27+0.72}_{-11.36-0.71}$ |
| $\overline{B}^0_s \to \Lambda\overline{\Lambda}$ | $14.90^{+6.42+1.97+7.58+0.61}_{-5.31-0\phantom{.00}-5.99-0.60}$ |  |  |
| $B^- \to p\overline{\Delta^{++}}$ | $6.21^{+3.01+0.58+8.77}_{-2.23-0\phantom{.00}-4.89}\pm 0.08$ | $\overline{B}^0_s \to p\overline{\Sigma^{*+}}$ | $1.84^{+0.89+0.17+2.60}_{-0.66-0\phantom{.00}-1.45}\pm 0$ |
|  | $(< 14)$ [8] |  |  |
| $B^- \to \Lambda\overline{\Delta^+}$ | $0.15^{+0.07+0.11+0.07}_{-0.05-0\phantom{.00}-0.05}\pm 0$ | $\overline{B}^0 \to \Lambda\overline{\Delta^0}$ | $0.14^{+0.07+0.10+0.06}_{-0.05-0\phantom{.00}-0.05}\pm 0$ |
|  | $(< 82)$ [9] |  | $(< 93)$ [9] |
| $\overline{B}^0 \to \Xi^-\overline{\Sigma^{*-}}$ | $1.49^{+0.66}_{-0.53}\pm 0^{+0.63}_{-0.52}\pm 0$ |  |  |
| $B^- \to \Delta^0\overline{p}$ | $2.19^{+1.05+0\phantom{.00}+0.92}_{-0.79-0.15-0.74}\pm 0.03$ | $\overline{B}^0_s \to \Delta^0\overline{\Lambda}$ | $2.59^{+1.27+0.03+1.01}_{-0.93-0\phantom{.00}-0.84}\pm 0$ |
|  | $(< 138)$ [8] |  |  |
| $B^- \to \Sigma^{*0}\overline{p}$ | $0.94^{+0.43+0\phantom{.00}+0.51}_{-0.33-0.24-0.40}\pm 0.001$ | $\overline{B}^0 \to \Sigma^{*+}\overline{p}$ | $2.25^{+0.93+0.58+0.93}_{-0.80-0\phantom{.00}-0.75}\pm 0$ |
|  | $(< 47)$ [9] |  | $(< 26)$ [9] |
| $\overline{B}^0 \to \Omega^-\overline{\Xi^-}$ | $3.47^{+1.54}_{-1.24}\pm 0^{+1.47}_{-1.21}\pm 0$ | $\overline{B}^0 \to \Xi^{*0}\overline{\Lambda}$ | $2.71^{+1.13+0.70+1.12}_{-0.97-0\phantom{.00}-0.90}\pm 0$ |
| $\overline{B}^0 \to \Delta^{++}\overline{\Delta^{++}}$ | $0\pm 0\pm 0\pm 0^{+0.004}_{-0}$ | $\overline{B}^0 \to \Delta^0\overline{\Delta^0}$ | $5.99^{+2.83+0.94+3.14}_{-2.15-0\phantom{.00}-2.47}\pm 0.13$ |
|  | $< 1.1\times 10^4$ [10] |  | $< 1.5\times 10^5$ [10] |
| $\overline{B}^0 \to \Sigma^{*-}\overline{\Sigma^{*-}}$ | $1.05^{+0.47}_{-0.37}\pm 0^{+0.45}_{-0.37}\pm 0.07$ |  |  |
| $B^- \to \Sigma^{*+}\overline{\Delta^{++}}$ | $21.48^{+8.92+5.53+8.86}_{-7.65-0\phantom{.00}-7.15}\pm 0.007$ | $B^- \to \Sigma^{*-}\overline{\Delta^0}$ | $6.06^{+2.68}_{-2.16}\pm 0^{+2.57}_{-2.12}\pm 0.005$ |
| $B^- \to \Xi^{*0}\overline{\Sigma^{*+}}$ | $24.26^{+10.44+3.21+9.87}_{-8.64\phantom{0}-0\phantom{.00}-8.13}\pm 0.01$ | $B^- \to \Omega^-\overline{\Xi^{*0}}$ | $15.49^{+6.86}_{-5.51}\pm 0^{+6.57}_{-5.41}\pm 0.01$ |
| $\overline{B}^0_s \to \Sigma^{*+}\overline{\Sigma^{*+}}$ | $6.49^{+2.69+1.67+2.67+0.77}_{-2.31-0\phantom{.00}-2.16-0.72}$ | $\overline{B}^0_s \to \Sigma^{*-}\overline{\Sigma^{*-}}$ | $5.48^{+2.43}_{-1.95}\pm 0^{+2.33+0.72}_{-1.92-0.67}$ |
| $\overline{B}^0_s \to \Xi^{*0}\overline{\Xi^{*0}}$ | $21.92^{+9.44+2.90+8.92+1.36}_{-7.81-0\phantom{.00}-7.35-1.32}$ | $\overline{B}^0_s \to \Omega^-\overline{\Omega^-}$ | $41.95^{+18.58}_{-14.93}\pm 0^{+17.81+1.79}_{-14.67-1.75}$ |

to be of the order of $10^{-8}$. Also note that the $\overline{B}^0_s \to \Omega^-\overline{\Omega^-}$ rate is predicted to be the highest rate.

Direct *CP* asymmetries of all $\overline{B}_q \to \mathscr{B}\overline{\mathscr{B}}$, $\mathscr{B}\overline{\mathscr{D}}$, $\mathscr{D}\overline{\mathscr{B}}$ and $\mathscr{D}\overline{\mathscr{D}}$ modes are explored. Results of *CP* asymmetries for modes with relatively good detectability in rates are highlighted in [4]. In particular, the direct *CP* asymmetry of $\overline{B}^0 \to p\overline{p}$ decay can be as large as ±50%, but the one for $B^- \to \Lambda\bar{p}$ is smaller and with opposite sign (see Fig. 2). Some of the *CP* asymmetries are small or vanishing. For $\overline{B} \to \mathscr{B}\overline{\mathscr{B}}$, $\Delta S = -1$ decays, $\overline{B}^0 \to \Xi^-\overline{\Sigma^-}$, $\overline{B}^0_s \to \Sigma^-\overline{\Sigma^-}$ and $\overline{B}^0_s \to \Xi^-\overline{\Xi^-}$ decays are pure penguin modes. For $\overline{B} \to \mathscr{B}\overline{\mathscr{D}}$, $\Delta S = 0$ decays, $\overline{B}^0 \to \Sigma^+\overline{\Sigma^{*+}}$ and $\overline{B}^0 \to \Xi^0\overline{\Xi^{*0}}$ decays are pure exchange modes. For $\overline{B} \to \mathscr{B}\overline{\mathscr{D}}$, $\Delta S = -1$ decays, $\overline{B}^0 \to \Sigma^-\overline{\Delta^-}$, $\overline{B}^0 \to \Xi^-\overline{\Sigma^{*-}}$, $\overline{B}^0_s \to \Sigma^-\overline{\Sigma^{*-}}$ and $\overline{B}^0_s \to \Xi^-\overline{\Xi^{*-}}$ decays are pure penguin modes and $\overline{B}^0_s \to p\overline{\Delta^+}$ and $\overline{B}^0_s \to n\overline{\Delta^0}$ decays are pure exchange modes. For $\overline{B} \to \mathscr{D}\overline{\mathscr{B}}$, $\Delta S = 0$ decays, $\overline{B}^0 \to \Xi^{*0}\overline{\Xi^0}$ and $\overline{B}^0 \to \Sigma^{*+}\overline{\Sigma^+}$ decays are pure exchange modes. For $\overline{B} \to \mathscr{D}\overline{\mathscr{B}}$, $\Delta S = -1$ decays, $\overline{B}^0 \to \Omega^-\overline{\Xi^-}$, $\overline{B}^0_s \to \Sigma^{*-}\overline{\Sigma^-}$, $\overline{B}^0 \to \Xi^{*-}\overline{\Sigma^-}$ and $\overline{B}^0_s \to \Xi^{*-}\overline{\Xi^-}$ decays are pure penguin modes, while $\overline{B}^0_s \to \Delta^+\overline{p}$ and $\overline{B}^0_s \to \Delta^0\overline{n}$ decays are pure



(a) (b)

Figure 2: Direct *CP* asymmetries of some interesting modes are plotted with respect to the penguin-tree relative strong phase $\phi$.

exchange modes. For $\overline{B} \to \mathscr{D}\overline{\mathscr{D}}$, $\Delta S = 0$ decays, $\overline{B}^0 \to \Omega^-\overline{\Omega^-}$ decay is a pure penguin annihilation mode. For $\overline{B} \to \mathscr{D}\overline{\mathscr{D}}$, $\Delta S = -1$ decays, $\overline{B}^0 \to \Sigma^{*-}\overline{\Delta^-}$, $\overline{B}^0 \to \Xi^{*-}\overline{\Sigma^{*-}}$, $\overline{B}^0 \to \Omega^-\overline{\Xi^{*-}}$, $\overline{B}^0_s \to \Sigma^{*-}\overline{\Sigma^{*-}}$, $\overline{B}^0_s \to \Omega^-\overline{\Omega^-}$ and $\overline{B}^0_s \to \Xi^{*-}\overline{\Xi^{*-}}$ decays are pure penguin modes, and the $\overline{B}^0_s \to \Delta^-\overline{\Delta^-}$ decay is a pure penguin annihilation mode. The *CP* asymmetries of the above modes are small, following from the hierarchy of the CKM factors, or vanishing. They can be added to the list of the tests of the Standard Model. Note that some of these modes have relatively good detectability in rates. These include, $\overline{B}^0_s \to \Xi^-\overline{\Xi^-}$, $\overline{B}^0 \to \Xi^-\overline{\Sigma^{*-}}$, $\overline{B}^0 \to \Omega^-\overline{\Xi^-}$, $\overline{B}^0_s \to \Sigma^{*-}\overline{\Sigma^{*-}}$ and $\overline{B}^0_s \to \Omega^-\overline{\Omega^-}$ decays, $\overline{B}^0_s \to \Xi^-\overline{\Xi^{*-}}$, $\overline{B}^0_s \to \Xi^{*-}\overline{\Xi^-}$, $\overline{B}^0 \to \Xi^{*-}\overline{\Sigma^{*-}}$ and $\overline{B}^0 \to \Omega^-\overline{\Xi^{*-}}$ decays, and $\overline{B}^0_s \to \Xi^{*-}\overline{\Xi^{*-}}$ decay, but some require $B_s$ tagging to search for its *CP* asymmetry. It will be interesting to search for these modes and use their *CP* asymmetries to search for New Physics. Furthermore, since these modes are rare decay modes and all of them are pure penguin modes, they are expected to be sensitive to New Physics contributions.

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