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Three-body charmless baryonic $\bar{B}_s^0$ decays

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ABSTRACT

We study for the first time the three-body charmless baryonic decays $\bar{B}_s^0 \to \bar{p}\Lambda M^+(p\bar{\Lambda}M^-)$, with $M = \pi, K$. We find that the branching ratios of $\bar{B}_s^0 \to (\bar{p}\Lambda K^+$ and $p\bar{\Lambda}K^-)$ and $\bar{B}_s^0 \to p\bar{\Lambda}\pi^-$ are $(5.1 \pm 1.1) \times 10^{-6}$ and $(2.8 \pm 1.5) \times 10^{-7}$, respectively, which agree with recent experimental results reported by the LHCb collaboration. In addition, we derive the relations $\mathcal{B}(\bar{B}_s^0 \to \bar{p}\Lambda K^+) \simeq (f_K/f_\pi)^2(\tau_{B_s^0}/\tau_{B^0})\mathcal{B}(\bar{B}^0 \to \bar{p}\Lambda\pi^+)$ and $\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}\pi^-)/\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}K^-) \simeq \mathcal{B}(B^- \to p\bar{p}\pi^-)/\mathcal{B}(B^- \to p\bar{p}K^-)$ to be confronted to future experimental measurements. The fact that all four processes $B_s^0, \bar{B}_s^0 \to p\bar{\Lambda}K^-, \bar{p}\Lambda K^+$ can occur opens the possibility of decay-time-dependent CP violation measurements in baryonic B decays, something that had not been realized before.

1. Introduction

In contrast with mesonic B decays, the decays of B mesons to baryonic final states have been observed to have unique signatures due to the baryon-pair ($\mathbf{B_1\bar{B}_2}$) formations, which reflect rich mechanisms for the hadronizations of the spinors. For example, the BaBar and Belle experiments at the B factories [1] reported typical three-body charmless baryonic B decay branching ratios $\mathcal{B}(B \to \mathbf{B_1\bar{B}_2}M) \simeq \mathcal{O}(10^{-6})$, and provided evidence for prominent peaks around $m_{\mathbf{B_1\bar{B}_2}} \simeq m_{\mathbf{B_1}} + m_{\mathbf{\bar{B}_2}}$ in the baryon–antibaryon spectra of baryonic B decays [2], which show that the $\mathbf{B_1\bar{B}_2}$ formations favour the threshold area. However, in two-body decays $B \to \mathbf{B_1\bar{B}_2}$, there is no large energy release from the recoiled meson [3], such that the total energy of $\mathbf{B_1\bar{B}_2}$ is at the m_B scale, which definitely deviates from the threshold area [4]. As a result, $\mathcal{B}(B \to \mathbf{B_1\bar{B}_2})$ are seen to be small, around 10^{-8}–10^{-7} [5–7]. Furthermore, the angular distribution asymmetry $\mathcal{A}_\theta$ of $\bar{B}^0 \to \bar{p}\Lambda\pi^+$ has been measured to have an unexpectedly large value of $(-41 \pm 11 \pm 3)\%$, indicating significant interference as a result of the baryonic form factors [9,10]. The same behaviour has been observed in decays to final states with open charm, for example $\mathcal{A}_\theta(\bar{B}^0 \to \Lambda\bar{p}D^{*+}) = (55 \pm 17)\%$ [8].

The aforementioned observations in $\bar{B}^0/B^- \to \mathbf{B_1\bar{B}_2}(M)$ decays may also hold for $\bar{B}_s^0 \to \mathbf{B_1\bar{B}_2}(M)$ decays now experimentally accessible to the LHCb collaboration [11,12]. Nonetheless, baryonic $\bar{B}_s^0$ decays are not trivially related to baryonic $\bar{B}^0$ and B^- decays. For example, replacing $(\bar{u}, \bar{d})$ by $\bar{s}$ in $\bar{B}^0/B^-$, one may approximately infer that

$$\begin{aligned}
&\mathcal{B}(\bar{B}_s^0 \to \bar{p}\Lambda K^+) \simeq \mathcal{B}(\bar{B}^0 \to \bar{p}\Lambda\pi^+)\,,\\
&\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}\pi^-) \simeq \mathcal{B}(B^- \to p\bar{p}\pi^-)\,,\\
&\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}K^-) \simeq \mathcal{B}(B^- \to p\bar{p}K^-)\,, \qquad (1)
\end{aligned}$$

which will be shown to be mostly incorrect, except for the first relation. We will also demonstrate that the recent first observation, made by the LHCb collaboration, of a baryonic $\bar{B}_s^0$ decay, namely $\bar{B}_s^0 \to p\bar{\Lambda}K^-$, and the measurement of its branching ratio [13], combines in reality the branching ratios of $\bar{B}_s^0 \to p\bar{\Lambda}K^-$ and $\bar{B}_s^0 \to \bar{p}\Lambda K^+$.

2. Formalism

The decay $\bar{B}^0 \to \bar{p}\Lambda\pi^+$ is flavour specific, unlike the similar mode of the $\bar{B}_s^0$ meson, which can decay to both $\bar{p}\Lambda K^+$ and $p\bar{\Lambda}K^-$ final states. The latter three-body baryonic $\bar{B}_s^0$ decays proceed through different configurations as demonstrated in the Feynman diagrams in Fig. 1. Specifically, the baryon pairs involve quark currents and B meson transitions as depicted in Figs. 1(a,b) and (c,d), respectively.

The amplitudes can be factorized in terms of the effective Hamiltonian at the quark level [14] as [9,15–18]

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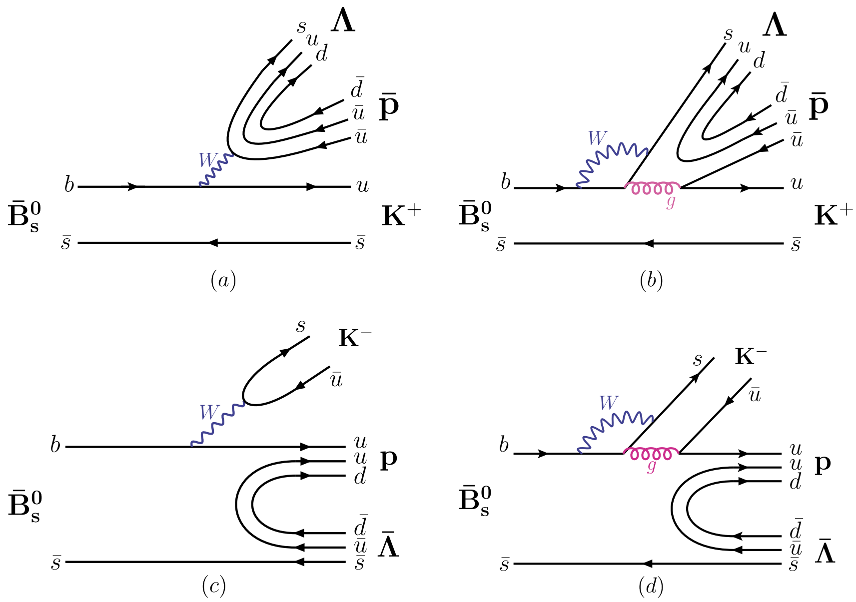

Fig. 1. Feynman diagrams for three-body baryonic $\bar{B}^0_s$ decays, where (a,b) depict $\bar{B}^0_s \to \bar{p}\Lambda K^+$ while (c,d) depict $\bar{B}^0_s \to p\bar{\Lambda}K^-$.

$$
\begin{aligned}
&\mathcal{A}(\bar{B}^0_s \to \bar{p}\Lambda K^+) = \\
&\frac{G_F}{\sqrt{2}}\Big\{\alpha_1\langle \bar{p}\Lambda|(\bar{s}u)_{V-A}|0\rangle\langle K^+|(\bar{u}b)_{V-A}|\bar{B}^0_s\rangle \\
&\quad + \alpha_6\langle \bar{p}\Lambda|(\bar{s}u)_{S+P}|0\rangle\langle K^+|(\bar{u}b)_{S-P}|\bar{B}^0_s\rangle\Big\}, \\
&\mathcal{A}(\bar{B}^0_s \to p\bar{\Lambda}K^-) = \\
&\frac{G_F}{\sqrt{2}}\Big\{\alpha_1\langle K^-|(\bar{s}u)_{V-A}|0\rangle\langle p\bar{\Lambda}|(\bar{u}b)_{V-A}|\bar{B}^0_s\rangle \\
&\quad + \alpha_6\langle K^-|(\bar{s}u)_{S+P}|0\rangle\langle p\bar{\Lambda}|(\bar{u}b)_{S-P}|\bar{B}^0_s\rangle\Big\}, \qquad (2)
\end{aligned}
$$

with $\alpha_1 = V_{ub}V^*_{us}a_1 - V_{tb}V^*_{ts}a_4$ and $\alpha_6 = V_{tb}V^*_{ts}2a_6$, where G_F is the Fermi constant, V_{ij} are the CKM matrix elements, $(\bar{q}_1 q_2)_{V(A)}$ and $(\bar{q}_1 q_2)_{S(P)}$ stand for $\bar{q}_1\gamma_\mu(\gamma_5)q_2$ and $\bar{q}_1(\gamma_5)q_2$, respectively, and $a_{1(4,6)} \equiv c^{eff}_{1(4,6)} + c^{eff}_{2(3,5)}/N^{eff}_c$ are composed of the effective Wilson coefficients c^{eff}_i defined in Ref. [14] with N^{eff}_c the effective colour number, ranging between 2 and ∞ to account for the non-factorizable effects in the generalized factorization approach. The amplitude $\mathcal{A}(\bar{B}^0_s \to p\bar{\Lambda}\pi^-)$ is obtained from $\mathcal{A}(\bar{B}^0_s \to p\bar{\Lambda}K^-)$ of Eq. (2) replacing the strange quark by the down quark.

In our calculation, the matrix elements of $\bar{B}^0_s \to \bar{p}\Lambda K^+$ in Eq. (2) are expressed as [15,16]

$$
\begin{aligned}
&\langle M|\bar{q}\gamma^\mu b|B\rangle = (p_B + p_M)^\mu F^{BM}_1 + \frac{m^2_B - m^2_M}{t}q^\mu(F^{BM}_0 - F^{BM}_1), \\
&\langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|\bar{q}_1\gamma_\mu q_2|0\rangle = \bar{u}\left[F_1\gamma_\mu + \frac{F_2}{m_{\mathbf{B_1}} + m_{\bar{\mathbf{B}}_\mathbf{2}}}i\sigma_{\mu\nu}q_\mu\right]v, \\
&\langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|\bar{q}_1\gamma_\mu\gamma_5 q_2|0\rangle = \bar{u}\left[g_A\gamma_\mu + \frac{h_A}{m_{\mathbf{B_1}} + m_{\bar{\mathbf{B}}_\mathbf{2}}}q_\mu\right]\gamma_5 v, \\
&\langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|\bar{q}_1 q_2|0\rangle = f_S\bar{u}v,\ \langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|q_1\gamma_5 q_2|0\rangle = g_P\bar{u}\gamma_5 v, \qquad (3)
\end{aligned}
$$

with $q = p_B - p_M = p_{\mathbf{B_1}} + p_{\bar{\mathbf{B}}_\mathbf{2}}$, $t \equiv q^2$, $p = p_B - q$, and u (v) the (anti-)baryon spinor, where $F^{BM}_{0,1}$ are the form factors for the $B \to M$ transition, and $F_{1,2}$, g_A, h_A, f_S, and g_P the timelike baryonic form factors. For $\bar{B}^0_s \to p\bar{\Lambda}K^-$, besides $\langle M|\bar{q}_1\gamma^\mu\gamma_5 q_2|0\rangle = -if_M p^\mu_M$ with f_M the decay constant, the matrix elements of the $B \to \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}$ transition are parameterized as [9,17]

$$
\begin{aligned}
&\langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|\bar{q}\gamma_\mu b|B\rangle = i\bar{u}[g_1\gamma_\mu + g_2 i\sigma_{\mu\nu}p^\nu + g_3 p_\mu + g_4 q_\mu \\
&\qquad + g_5(p_{\bar{\mathbf{B}}_\mathbf{2}} - p_{\mathbf{B_1}})_\mu]\gamma_5 v, \\
&\langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|\bar{q}\gamma_\mu\gamma_5 b|B\rangle = i\bar{u}[f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}p^\nu + f_3 p_\mu + f_4 q_\mu \\
&\qquad + f_5(p_{\bar{\mathbf{B}}_\mathbf{2}} - p_{\mathbf{B_1}})_\mu]v, \\
&\langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|\bar{q}b|B\rangle = i\bar{u}[\bar{g}_1\not{p} + \bar{g}_2(E_{\bar{\mathbf{B}}_\mathbf{2}} + E_{\mathbf{B_1}}) + \bar{g}_3(E_{\bar{\mathbf{B}}_\mathbf{2}} - E_{\mathbf{B_1}})]\gamma_5 v, \\
&\langle \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}|\bar{q}\gamma_5 b|B\rangle = i\bar{u}[\bar{f}_1\not{p} + \bar{f}_2(E_{\bar{\mathbf{B}}_\mathbf{2}} + E_{\mathbf{B_1}}) + \bar{f}_3(E_{\bar{\mathbf{B}}_\mathbf{2}} - E_{\mathbf{B_1}})]v, \qquad (4)
\end{aligned}
$$

where $g_i(f_i)$ $(i = 1, 2, ..., 5)$ and $\bar{g}_j(\bar{f}_j)$ $(j = 1, 2, 3)$ are the $B \to \mathbf{B_1}\bar{\mathbf{B}}_\mathbf{2}$ transition form factors. The form factors in Eqs. (3) and (4) are momentum dependent. Explicitly, $F^{BM}_{0,1}$ are given by [19]

$$
\begin{aligned}
&F^{BM}_1(t) = \frac{F^{BM}_1(0)}{(1 - \frac{t}{M^2_V})(1 - \frac{\sigma_{11}t}{M^2_V} + \frac{\sigma_{12}t^2}{M^4_V})}, \\
&F^{BM}_0(t) = \frac{F^{BM}_0(0)}{1 - \frac{\sigma_{01}t}{M^2_V} + \frac{\sigma_{02}t^2}{M^4_V}}. \qquad (5)
\end{aligned}
$$

In perturbative QCD counting rules, the baryonic form factors depend on $1/t^n$ as the leading-order expansion [9,17,20,21], given by

$$
\begin{aligned}
&F_1 = \frac{\bar{C}_{F_1}}{t^2},\ g_A = \frac{\bar{C}_{g_A}}{t^2},\ f_S = \frac{\bar{C}_{f_S}}{t^2},\ g_P = \frac{\bar{C}_{g_P}}{t^2}, \\
&f_i = \frac{D_{f_i}}{t^3},\ g_i = \frac{D_{g_i}}{t^3},\ \bar{f}_i = \frac{D_{\bar{f}_i}}{t^3},\ \bar{g}_i = \frac{D_{\bar{g}_i}}{t^3}, \qquad (6)
\end{aligned}
$$

where $\bar{C}_i = C_i[\ln(t/\Lambda^2_0)]^{-\gamma}$ with $\gamma = 2.148$ and $\Lambda_0 = 0.3$ GeV.

3. Numerical results and discussions

For the numerical analysis, the theoretical inputs of the CKM matrix elements in the Wolfenstein parameterization are given by [1]