B-meson decays to baryon-antibaryon pairs

Gurpreet Kaur and M. P. Khanna
Department of Physics, Panjab University, Chandigarh 160 014, India
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We study B-meson decays to baryon-antibaryon pairs in the factorization formalism. In view of the large momentum transfer involved in these decays, the asymptotic behavior of the form factors is considered. Branching ratios and decay widths for some of the modes are calculated. Final-state-interaction effects may be important for these decays.

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I. INTRODUCTION

Recently, B-meson physics has received much attention. As the strong-interaction effects are minimized here, their study may enable a comprehensive understanding of many of the important issues of present-day physics—the interplay of strong and weak interactions, parity, and CP violation.

Because of the large mass of B mesons, for the first time we have the possibility of mesons decaying into baryons and, hence, theoretical interest in these modes. Baryonic B decays have been studied recently in the symmetry approach [1], the pole model [2,3] and the QCD sum-rule method [4].

In this Brief Report, we examine B-meson decays into baryon-antibaryon pairs in the factorization formalism [5]. In view of the large momentum transfer ($\approx 25\ \text{GeV}^2$) involved in these decays, we refer to the asymptotic behavior of form factors discussed by Brodsky, Lepage, and Zaidi [6]. In particular, we make calculations of branching ratios for some of the transitions of B_u and B_d into Kobayashi-Maskawa- (KM) allowed and Cabibbo- (C) allowed decays without a strange quark in the final state (Table I). To be more general we consider both the $(\frac{1}{2}^+,\overline{\frac{1}{2}}^+)$ and $(\frac{1}{2}^+,\overline{\frac{3}{2}}^+)$ baryons in the final state.

The flavor flow diagrams are introduced in Sec. II. In Sec. III we discuss the factorization assumption and the asymptotic behavior of form factors. Our results are discussed in Sec. IV, while our conclusions are presented in Sec. V.

II. QUARK DIAGRAMS FOR B DECAYS TO BARYON-ANTIBARYON PAIRS

As has been discussed by Korner [7], the various flavor diagrams contributing to baryonic decays of bottom mesons include (i) penguin contributions, (ii) W-exchange contributions, and (iii) W-decay contributions. The penguin contributions are expected to be strongly suppressed [8], although they have been discussed as a possible source of charmless B-meson decays [9]. Similarly, the W-exchange contributions are either zero or color-suppressed [7]. The W-decay contributions corresponding to an effective charged-current interaction and the associated effective neutral-current interaction are shown in Fig. 1.

It has been emphasized by Buras, Gerard, and Ruckl [10] that to leading order in $1/N$ expansion, these diagrams can be factorized by a Fierz transformation with a color factor of $1/N$ for both. Obviously, there are no external W-emission diagrams contributing to two-body baryonic decays of B mesons, although they may contribute to many-particle decays [3].

TABLE I. Values of decay width, branching ratio (in terms of $\alpha=a|V_{ub}/V_{cb}|$), and Γ_{PV}/Γ_{PC}.

Decay mode	Decay width ($10^6 a^2\ \text{sec}^{-1}$)	Branching ratio ($10^{-8}\alpha^2$)	Γ_{PV}/Γ_{PC}
$\bar{B}^0\to p\bar{p}$	$1.45\|V_{ub}V_{ud}\|^2$	1.039	0.0
$B^-\to n\bar{p}$	$5.56\|V_{ub}V_{ud}\|^2$	3.97	$0.0(\sim 10^{-6})$
$\bar{B}^0\to n\bar{n}$	$1.47\|V_{ub}V_{ud}\|^2$	1.05	0.0
$\bar{B}^0\to\Lambda_c^+\bar{p}$	$7.80\|V_{bc}V_{ud}\|^2$	$5.58(a/\alpha)^2$	0.116
$\bar{B}^0\to\Sigma_c^+\bar{p}$	$0.107\|V_{bc}V_{ud}\|^2$	$0.154(a/\alpha)^2$	0.0
$\bar{B}^0\to\Sigma_c^0\bar{n}$	$0.216\|V_{bc}V_{ud}\|^2$	$0.077(a/\alpha)^2$	0.0
$B^-\to\bar{\Delta}^{++}p$	$2.26\|V_{ub}V_{ud}\|^2$	1.616	0.095
$B^-\to n\bar{\Delta}^+$	$0.846\|V_{ub}V_{ud}\|^2$	0.604	0.171
$B^-\to\Delta^0\bar{p}$	$0.806\|V_{ub}V_{ud}\|^2$	0.576	0.052
$\bar{B}^0\to p\bar{\Delta}^+$	$0.76\|V_{ub}V_{ud}\|^2$	0.542	0.052
$\bar{B}^0\to n\bar{\Delta}^0$	$0.76\|V_{ub}V_{ud}\|^2$	0.542	0.171

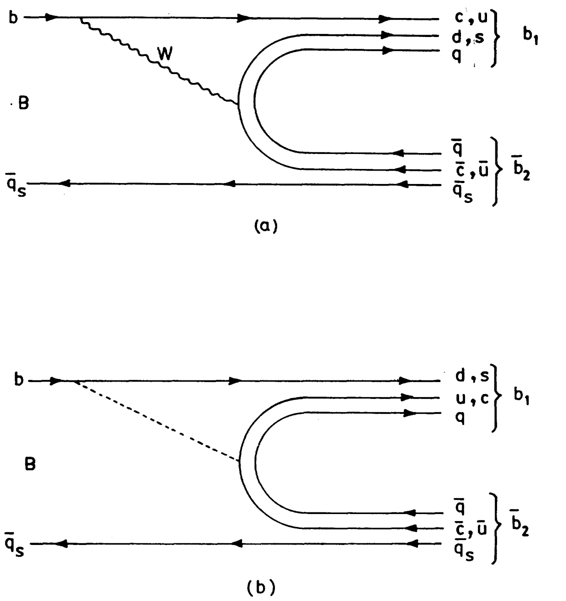

FIG. 1. (a) Effective charge-current contribution through W-decay mechanism. (b) Effective neutral-current interaction.

III. THE FACTORIZATION HYPOTHESIS

In this hypothesis, one assumes that the matrix element of a product of operators may be expressed as the product of matrix elements of the same operators. More recently, Dugan and Grinstein [11] have argued for the validity of this hypothesis in certain kinematic limits. In addition, factorization seems to work phenomenologically for the mesonic decay of heavy mesons [12]. In this work, we extend the approach to the baryonic modes of B mesons.

It is emphasized that each of the B-meson decay modes into baryon-antibaryon pairs can receive only one contribution from the effective Hamiltonian, corresponding to the single "factorization" of the decay matrix element into mesonic and baryonic matrix element components. Thus, writing the effective interaction in the form of a Wick-ordered product of hadronic currents one gets

$$H_{\text{eff}}=\frac{G_F}{\sqrt{2}}V_{cj}^{*}V_{kl}\begin{Bmatrix} a_1(\bar{k}l)_H(\bar{j}c)_H \\ a_2(\bar{k}c)_H(\bar{j}l)_H \\ a[(\bar{k}l)_H(\bar{j}c)_H+(\bar{k}c)_H(\bar{j}l)_H] \end{Bmatrix} \quad (1)$$

The index H indicates that $(\bar{k}l)$ is the hadron field operator rather than a quark current. (c,k) and (j,l) stand for $+\frac{2}{3}$ charge quarks and $-\frac{1}{3}$ quarks, respectively. Instead of the scale-dependent QCD coefficients C_1, C_2 [12,13], new scale-independent coefficients a, a_1, a_2 are introduced. They are real by time-reversal invariance. These coefficients are different from those introduced in mesonic decays [14] owing to the fact that there are no external W-emission diagrams contributing to baryonic decays. By assuming factorization of (1) at the scale of the b quark mass, one gets the following relation between (a,a_i) and the coefficients C_i:

$$a\simeq\xi(C_1+C_2),\quad a_1\simeq\xi C_1,\quad a_2\simeq\xi C_2\ . \quad (2)$$

The color factor $\xi=1/N$ arises from the color mismatch in forming color singlets after Fierz transformation. Three classes of decays can be distinguished: (i) decays determined by parameter a_1 and receiving contribution from Fig. 1(a) only, (ii) decays determined by parameter a_2 and receiving contribution from Fig. 1(b) only, and (iii) decays in which C_1 and C_2 interfere, i.e., decays determined by the parameter a and receiving contribution from both the diagrams of Fig. 1. It so happens that the decays we have considered involve the parameter a only. In the following we shall take (a,a_i) as free parameters to be determined by experiments.

In the factorization approximation, the decay amplitude for $B\to b_1\bar{b}_2$ is given by

$$\langle b_1\bar{b}_2|H_W|B\rangle=\frac{G_F}{\sqrt{2}}V_{cj}^{*}V_{kl}(a/a_1/a_2)\times\langle b_1\bar{b}_2|J_\mu|0\rangle\langle 0|J_\mu|B\rangle\ . \quad (3)$$

The meson matrix element is

$$\langle 0|J_\mu|B\rangle=f_BP^\mu,\quad\text{where } f_B=180\text{ MeV}\ , \quad (4)$$

and with the first-order parametrization for the baryon matrix element

$$\langle b_1\bar{b}_2|(q\bar{q})_H|0\rangle=\bar{v}(p')[i\gamma_\mu(f_1+g_1\gamma_5)]u(p)\ , \quad (5)$$

the decay amplitude (3) becomes

$$\langle b_1\bar{b}_2|H_W|B\rangle=\frac{G_F}{\sqrt{2}}V_{cj}^{*}V_{kl}f_B(a/a_1/a_2)\bar{v}(p')\times[(m_{\bar{B}}-m_B)f_1+(m_{\bar{B}}+m_B)g_1\gamma_5]u(p)\ . \quad (6)$$

The first term in (6) represents the parity-violating amplitude and the second term corresponds to the parity-conserving amplitude. f_1,g_1 are the vector and axial-vector form factors, respectively.

For numerical estimates, all we now require are the form factors at momentum transfer $Q^2=m_B^2$, all other variables being known. The dipole-type form factors at $Q^2\neq 0$ have been considered by Körner [7]. Since we are working in the range of high Q^2, it seems more appropriate to take into consideration the asymptotic behavior of form factors. Detailed perturbative QCD predictions for the power law and anomalous logarithmic behavior of meson and baryon form factors to leading order in $\alpha_s(Q^2)$ and m/Q are given in Refs. [15,16]. For the present purpose, we refer to the work of Brodsky, Lepage, and Zaidi [6] on expressing the octet and decuplet form factors as linear combinations of proton and neutron magnetic form factors.

An important feature of the perturbative QCD predictions is that all the helicity-conserving electroweak form factors involving only nucleons can be expressed as linear combinations of just two baryon form factors $G_{\uparrow\uparrow}(Q^2)$ and $G_{\uparrow\downarrow}(Q^2)$ corresponding to amplitudes in which the current interacts with a valence quark with helicity parallel or antiparallel to the helicity of the nucleon, respectively. Thus, the form factor for $AX^*\to B$ with $h_A=\pm\frac{1}{2}$ $(=h_B)$ and with $X=\gamma$, W, or Z is defined as

$$G^{\pm}(Q^2)_{AX^*\to B}=e^{\pm}_{\uparrow\uparrow}G^{AB}_{\uparrow\uparrow}(Q^2)+e^{\pm}_{\uparrow\downarrow}G^{AB}_{\uparrow\downarrow}(Q^2)\ , \qquad (7)$$

where the constants $e_{\uparrow\uparrow}$ and $e_{\uparrow\downarrow}$ are the sums of electroweak charges carried by valence quarks in the baryon with helicities parallel and antiparallel, respectively, to the baryon's helicity. They are determined solely by the flavor wave functions of the baryons A and B and by the flavor spin structure of the electroweak currents. The QCD dynamics is contained in the form factors $G^{AB}_{\uparrow\uparrow}$ and $G^{AB}_{\uparrow\downarrow}$,

$$G^{AB}_{\uparrow\uparrow(\uparrow\downarrow)}(Q^2)=\left[\frac{16}{3}\frac{\alpha_s(Q^2)}{Q^2}\right]^2\int_0^1[dx][dy]\phi^*_B(y_i,Q)T_{\uparrow\uparrow(\uparrow\downarrow)}(x_i,y_i,\alpha_s(Q^2))\phi(x_i,Q)\ , \qquad (8)$$

which are independent of the current (i.e., of X^*). The form factors $G^{\pm}$ are defined such that the expectation value of electroweak current between nucleon states is

$$\langle p'|J_\mu|p\rangle=v(p')\left[\gamma_\mu\frac{1+\gamma_5}{2}G^{(+)}(Q^2)+\gamma_\mu\frac{1-\gamma_5}{2}G^{(-)}(Q^2)\right]u(p)\ . \qquad (9)$$

These form factors dominate at $Q^2\to\infty$, all others being suppressed by powers of m/Q.

Finally, the form factors $G_{\uparrow\uparrow}$ and $G_{\uparrow\downarrow}$ are related to the nucleon form factors as

$$G^p_M=G_{\uparrow\uparrow},\quad G^n_M=-\frac{G_{\uparrow\uparrow}}{3}+\frac{G_{\uparrow\downarrow}}{3}\ . \qquad (10)$$

Following the above formalism, the required vector and axial-vector form factors for all decays can be expressed in terms of G^n_M and G^p_M. The numerical value for G^p_M at $|Q^2|\simeq 20$ GeV^2 has been estimated by Chernyak and Zhitnitsky [17] as

$$Q^4G^p_M(Q^2)\simeq 1.1\ \text{GeV}^2\ , \qquad (11)$$

and the ratio of the neutron to the proton form factors at $|Q^2|\simeq 20$ GeV^2 is

$$G^n_M(Q^2)/G^p_M(Q^2)\simeq -0.5\ . \qquad (12)$$

The form factors for other decays may be obtained by invoking symmetry relations or by explicit calculation through wave functions. These computed values of decay widths are compared with the total width:

$$\Gamma_{\text{total}}\simeq 1.4\times 10^2|V_{bc}V_{ud}|^2\times(10^{12}\ \text{sec}^{-1})\ . \qquad (13)$$

The corresponding decay widths and branching-ratio estimates are listed in Table I along with the ratio Γ_{PV}/Γ_{PC} (the ratio of parity-violating to parity-conserving widths).

IV. DISCUSSION OF THE RESULTS

We have considered B-meson decays into baryon-antibaryon pairs in the factorization approach. The computed values of branching ratios in Table I compare with the results obtained by Körner [7], although we use a different formalism for form factors. However, these predictions are smaller than the pole-model calculations made by Jarfi *et al.* [3].

It should be mentioned that except for the B decays involving nucleons in the final state, all other modes involve particles of different isospin. Consequently, the role played by final-state interactions (FSI's) becomes important. FSI's affect the amplitude in two ways: if the final-state particles scatter elastically, then the weak amplitude acquires a phase equal to the elastic scattering phase and, second, the amplitude itself may be modulated. The extent of modulation depends on the behavior of the scattering phase shift in the entire region through a principal-part integration in Omne's function [18]. Elastic FSI's become important when the final state in the decay process involves more than one isospin. Interference can then occur leading to large FSI effects.

In view of the sparse data on baryonic modes a direct comparison with experiment is not yet possible. Our numerical results for $(\frac{1}{2}^+,\bar{\frac{1}{2}}^+)$ decays are well within (in fact rather lower than) the present range of experimental limit [19],

$$B(\bar{B}^0\to p\bar{p})<4\times 10^{-5}\ ,$$
$$B(\bar{B}^0\to p\bar{p}\pi^-\pi^+)=(6.0\pm 3.0)\times 10^{-4}\ ,$$

but their modification by FSI's is expected to bring the results closer to the experimental range. As the experimental data on these decays are too primeval to enable definite conclusions, it is hoped that the factorization method modified by FSI's may work reasonably well for two-body baryonic modes of B mesons. It may be mentioned that the factorization formalism of perturbative QCD for exclusive reactions at large momentum transfer, when applied to B-meson decays into light pseudoscalar mesons, has also yielded similar results [20].

An important way to test factorization involves the measurement of the ratio Γ_{PV}/Γ_{PC}. It is seen that Γ_{PV} goes to zero for N decays, and in other cases also it is very small. This happens due to the mass difference term in the PV amplitude. The results are in contrast with pole-model calculations and may be important for discerning the true picture.

Before concluding this section we would like to make one point concerning the parameter ξ. In the charm sector, the comparison of the calculated values with the available data suggests that ξ lies in the range 0.10 ± 0.15 [21], which is consistent with the naive value of $\frac{1}{3}$ and with zero. Also, it has been pointed out by Stech [22] that $\xi=0$ seems to describe the energetic two-body mesonic decays of B mesons. However, here it seems pertinent that ξ should have a value different from zero.

V. CONCLUSIONS

We have applied the factorization method to two-body baryon decays of B mesons. But this method alone predicts rather low values of branching ratios, probably due to the steep fall in the form factors at large Q^2 and also because only the color-suppressed terms contribute. FSI effects are important for these decays, and it is hoped that this modification may result in a better agreement with experiment. Also, this simple approach should work reasonably well for $(\frac{1}{2}^+, \frac{3}{2}^+)$ modes where the pole model predicts higher values.

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