Test of factorization hypothesis from exclusive nonleptonic B decays

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(Received 6 July 2001; published 2 May 2002)

We investigate the possibility of testing the factorization hypothesis in nonleptonic exclusive decays of the B meson. In particular, we consider the nonfactorizable $\overline{B}^0 \to D^{(*)+} D_s^{(*)-}$ modes and $\overline{B}^0 \to D^{(*)+}(\pi^-,\rho^-)$ known as well-factorizable modes. By taking the ratios $\mathcal{B}(\overline{B}^0 \to D^{(*)+} D_s^{(*)-})/\mathcal{B}[\overline{B}^0 \to D^{(*)+}(\pi^-,\rho^-)]$, we find that under the present theoretical and experimental uncertainties there is no evidence for the breakdown of the factorization description for heavy-heavy decays of the B meson.

DOI: 10.1103/PhysRevD.65.097503 PACS number(s): 13.20.He

Nonleptonic decays of heavy mesons are very important weak processes for the determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements [1] and the understanding of the CP violation mechanism. Nonleptonic decays of B mesons, however, are complicated processes due to their inherent hadronic nature and final-state interactions.

A simple formulation of the decay amplitude, the so-called naive factorization scheme [2,3], has been widely used without full theoretical justification. And its phenomenological extension, the generalized factorization scheme, with process-dependent quantities from penguin effects and nonfactorizable contributions, has been also widely used in the literature [4,5]. In this latter scheme, the nonfactorizable effects are contained in the effective color number, $N_c^{\rm eff}$, which is a free parameter [4,6] of the scheme; the value of $N_c^{\rm eff}$ was adjusted to ∞ for D decays and to 2 or 5 depending on the chiral structure of B decays.

Recently, much progress has been made [7,8] towards understanding nonleptonic decay processes by separating out short-distance physics from long-distance effects in the well-defined manner; Beneke *et al.* [7] proved the validity of factorization for the B-meson decay amplitude in the context of the perturbative QCD formalism. They showed that when a B meson decays weakly to a heavy meson and emits a light meson, the decay amplitude factorizes in the same form as the naive factorization formula, but with calculable coefficients in the heavy quark limit. In the case of a B meson decaying to a light meson rather than a heavy one, according to their formalizm, a contribution by a hard spectator quark is added to the amplitude, therefore the total amplitude is still factorizable. However, for B decays to a heavy or light meson emitting a heavy meson, their amplitudes are not written as factorized forms, since the color transparency arguments cannot be applied for such decays.

Though the factorization of the decay amplitude for a B meson decaying to heavy-heavy mesons has not been justified, there have been many calculations using the factorized formula in the literature [5,9,10]. Within the naive factorization scheme, Luo and Rosner [10] calculated the branching ratios of the B-meson decays, $\overline{B}^0 \to D^{(*)+} D_s^{(*)-}$, after extracting the values of $|V_{cb}|$ and the slope of the universal Isgur-Wise form factor ρ^2, by comparing the decay rates of $\overline{B}^0 \to D^{(*)+}(\pi^-,\rho^-)$ with a differential distribution of $\overline{B}^0 \to D^{(*)+} l^- \overline{\nu}_l$ measured by the CLEO Collaboration [11].

Here we test the generalized factorization scheme for the color-favored B-meson decay to heavy-heavy mesons by comparing with the B decay to heavy-light mesons. The selected decay processes are $\overline{B}^0 \to D^{(*)+} D_s^{(*)-}$ for heavy-heavy and $\overline{B}^0 \to D^{(*)+}(\pi^-,\rho^-)$ for heavy-light, whose experimental branching ratios are well known. Compared to the work of Luo and Rosner, in which the authors used the naive factorization scheme neglecting penguin effects, we include here penguin effects and take ratios of the decay rates to reduce the form factor dependence and cancel the CKM matrix elements. Here we investigate the validity of the factorization hypothesis by taking ratios of branching fractions of *presumably* nonfactorizable $\overline{B}^0 \to D^{(*)+} D_s^{(*)-}$ modes to factorizable $\overline{B}^0 \to D^{(*)+}(\pi^-,\rho^-)$ modes.

Based on the generalized factorization formalism, the decay amplitudes of our interest are expressed as

$$A(\overline{B}^0 \to D^{(*)+} M^-) = \frac{G_F}{\sqrt{2}} V_{cb} V^*_{qq'} \tilde{a}(D^{(*)} M)$$
$$\langle M^- | \overline{q'} \gamma^\mu (1-\gamma_5) q | 0 \rangle \langle D^{(*)+} | \overline{c} \gamma_\mu (1-\gamma_5) b | \overline{B}^0 \rangle, \quad (1)$$

where $q(q') = u(d)$ for $M = \pi,\rho$ and $q(q') = c(s)$ for $D_s^{(*)}$. The coefficient $\tilde{a}$ includes penguin effects and possible nonfactorizable contributions in the generalized factorization scheme. They are given, neglecting the W-exchange diagram and using $V_{tb}V^*_{ts} \cong -V_{cb}V^*_{cs}$, as

$$\tilde{a}(D^{(*)}(\pi,\rho)) = a_1,$$
$$\tilde{a}(DD_s) = a_1 \left(1 + \frac{a_4 + a_{10}}{a_1} + 2\frac{a_6+a_8}{a_1} \frac{m_{D_s}^2}{(m_b - m_c)(m_c + m_s)} \right),$$
$$\tilde{a}(D^* D_s) = a_1 \left(1 + \frac{a_4 + a_{10}}{a_1} - 2\frac{a_6+a_8}{a_1} \frac{m_{D_s}^2}{(m_b + m_c)(m_c + m_s)} \right), \quad (2)$$

$$\tilde{a}(D^{(*)}D_s^*) = a_1[1+(a_4+a_{10})/a_1],$$

where a_j's represent conventional effective parameters defined as $a_{2i} = c_{2i}^{\mathrm{eff}} + c_{2i-1}^{\mathrm{eff}}/N_c^{\mathrm{eff}}$ and $a_{2i-1} = c_{2i-1}^{\mathrm{eff}} + c_{2i}^{\mathrm{eff}}/N_c^{\mathrm{eff}}$. Using the numerical values of a_j's of Ref. [9], the effective parameters $\tilde{a}$ defined above are related to a_1 by

$$|\tilde{a}(B\to DD_s)| = 0.847a_1, \quad |\tilde{a}(B\to D^*D_s)| = 1.037a_1, \tag{3}$$
$$|\tilde{a}(B\to D^{(*)}D_s^*)| = 0.962a_1,$$

where the values are obtained by choosing $N_c^{\mathrm{eff}}=2$ for $(V-A)(V-A)$ interactions (i.e., for operators $O_{1,2,3,4,9,10}$) and $N_c^{\mathrm{eff}}=5$ for $(V-A)(V+A)$ interactions (i.e., for operators $O_{5,6,7,8}$) [9]. We note that the ratios, $|\tilde{a}/a_1|$, are numerically very stable over different N_c^{eff} values; for example, the numerical deviations are less than a few % for $N_c^{\mathrm{eff}}=2$, 3, 5, and ∞. From the relations in Eq. (3), one can see that, at the amplitude level, the penguin contributions to $\overline{B}^0\to D^{*+}D_s^-$ decay ($\sim 3.7\%$) are much smaller than those for the $\overline{B}^0\to D^+D_s^-$ mode ($\sim 15.3\%$). In fact, the penguin effects on $\overline{B}^0\to D^+D_s^-$ decay are not small enough to be simply neglected. As previously mentioned, the penguin effects are neglected in the analyses of Ref. [10]. We will show that the inclusion of the penguin effect in the $\overline{B}^0\to D^+D_s^-$ mode improves substantially the theoretical prediction to the experimental value. For the $\overline{B}^0\to D^{*+}D_s^-$ decay mode, the penguin contribution can be neglected. This difference of the penguin contributions between the similar decay modes $\overline{B}^0\to D^+D_s^-$ and $\overline{B}^0\to D^{*+}D_s^-$ is due to the different chiral structure of the final states: $B\to D^*$ transitions occur through axial vector currents, while $B\to D$ through vector currents.

The ratios

$$\mathcal{R}_{D_s^{(*)}/(\pi,\rho)} \equiv \frac{\mathcal{B}(\overline{B}^0\to D^+D_s^{(*)-})}{\mathcal{B}[\overline{B}^0\to D^+(\pi^-,\rho^-)]}, \tag{4}$$

$$\tilde{\mathcal{R}}_{D_s^{(*)}/(\pi,\rho)} \equiv \frac{\mathcal{B}(\overline{B}^0\to D^{*+}D_s^{(*)-})}{\mathcal{B}[\overline{B}^0\to D^{*+}(\pi^-,\rho^-)]}, \tag{5}$$

are given as

$$\mathcal{R}_{D_s/\pi} = \left|\frac{\tilde{a}(DD_s)}{\tilde{a}(D\pi)}\right|^2 \left(\frac{f_{D_s}}{f_\pi}\right)^2 \left(\frac{p_c^{DD_s}}{p_c^{D\pi}}\right) \left(\frac{F_0^{BD}(m_{D_s}^2)}{F_0^{BD}(m_\pi^2)}\right)^2, \tag{6}$$

$$\mathcal{R}_{D_s^*/\rho} = \left|\frac{\tilde{a}(DD_s^*)}{\tilde{a}(D\rho)}\right|^2 \left(\frac{f_{D_s^*}}{f_\rho}\right)^2 \left(\frac{p_c^{DD_s^*}}{p_c^{D\rho}}\right)^3 \left(\frac{F_1^{BD}(m_{D_s^*}^2)}{F_1^{BD}(m_\rho^2)}\right)^2, \tag{7}$$

$$\tilde{\mathcal{R}}_{D_s/\pi} = \left|\frac{\tilde{a}(D^*D_s)}{\tilde{a}(D^*\pi)}\right|^2 \left(\frac{f_{D_s}}{f_\pi}\right)^2 \left(\frac{p_c^{D^*D_s}}{p_c^{D^*\pi}}\right)^3 \left(\frac{A_0^{BD^*}(m_{D_s}^2)}{A_0^{BD^*}(m_\pi^2)}\right)^2, \tag{8}$$

$$\tilde{\mathcal{R}}_{D_s^*/\rho} = \left|\frac{\tilde{a}(D^*D_s^*)}{\tilde{a}(D^*\rho)}\right|^2 \left(\frac{f_{D_s^*}}{f_\rho}\right)^2 \left(\frac{p_c^{D^*D_s^*}}{p_c^{D^*\rho}}\right) \left(\frac{m_{D_s^*}}{m_\rho}\right)^2 \times [A_1^{BD^*}(m_{D_s^*}^2)/A_1^{BD^*}(m_\rho^2)]^2 [H(m_{D_s^*}^2)/H(m_\rho^2)], \tag{9}$$

where p_c^{XY} is the center-of-mass momentum of the decay particles and we used $|V_{cs}^*/V_{ud}|=1$. Here the form factors have the following parametrization [3]:

$$\langle P'(p')|V_\mu|P(p)\rangle = \left(p_\mu + p'_\mu - \frac{m_P^2-m_{P'}^2}{q^2}q_\mu\right)F_1(q^2) + [(m_P^2-m_{P'}^2)/q^2]\,q_\mu F_0(q^2),$$
$$\langle V(p',\epsilon)|V_\mu|P(p)\rangle = \frac{2}{m_P+m_V}\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}p^\alpha p'^\beta V(q^2), \tag{10}$$
$$\langle V(p',\epsilon)|A_\mu|P(p)\rangle = i\Bigg[(m_P+m_V)\epsilon_\mu A_1(q^2) - \frac{\epsilon\cdot p}{m_P+m_V}(p+p')_\mu A_2(q^2) - 2m_V\frac{\epsilon\cdot p}{q^2}q_\mu[A_3(q^2)-A_0(q^2)]\Bigg],$$

where $q=p-p'$, $F_1(0)=F_0(0)$, $A_3(0)=A_0(0)$,

$$A_3(q^2) = \frac{m_P+m_V}{2m_V}A_1(q^2) - \frac{m_P-m_V}{2m_V}A_2(q^2),$$

and P,V denote the pseudoscalar and vector mesons, respectively. For $B\to V_1V_2$ decay [see Eq. (9)], three form factors $A_1(q^2)$, $A_2(q^2)$, and $V(q^2)$ contribute. Here we factored out the dominant one $A_1(q^2)$ and the other two are put in the function $H(q^2)$ defined as

$$H(q^2) = (a-bx)^2 + 2(1+c^2y^2), \tag{11}$$

with

$$a = \frac{m_B^2-m_1^2-m_2^2}{2m_1m_2}, \quad b = \frac{2m_B^2p_c^2}{m_1m_2(m_B+m_1)^2}, \tag{12}$$

$$c = \frac{2m_Bp_c}{(m_B+m_1)^2}, \quad x = \frac{A_2^{BV_1}(q^2)}{A_1^{BV_1}(q^2)}, \quad y = \frac{V^{BV_1}(q^2)}{A_1^{BV_1}(q^2)}, \tag{13}$$

where m_1 (m_2) is the mass of the vector meson V_1 (V_2). Using the above ratios Eqs. (6)–(9), one can, in principle, test the validity of factorization without having a dependence on CKM matrix elements. However, the analysis depends strongly on nonperturbative hadronic factors such as decay constants and form factors. $B\to D^{(*)}$ transition form factors are rather well-constrained and the uncertainty in their ratios would be rather moderate. In the following numerical analysis, we consider three models for the form factors of B

$\to D^{(*)}$ transitions: the Bauer-Stech-Wirbel (BSW) model [3], the Melikhov-Stech model [12], and the relativistic light-front (LF) quark model [13]. We check our choice of form-factor values, in particular F_0^{BD} and F_1^{BD}, against the experimental measurements of $\mathcal{B}(B^0 \to D^{(*)-}\pi^+)$ and $\mathcal{B}(B^0 \to D^{(*)-}l^+\nu)$ following the methods explained in Refs. [9,10]. The results are consistent well within the experimental uncertainties of $\mathcal{B}(B^0 \to D^{(*)-}\pi^+)$ [14] and the combined semileptonic and nonleptonic decay analysis predictions [10].

Another uncertainty comes from decay constants, especially $f_{D_s^{(*)}}$, which presently has large uncertainty. The Particle Data Group report [14] gives two distinct values depending on its decay modes:

$$f_{D_s^+} = 194 \pm 35 \pm 20 \pm 14 \ \text{MeV from } D_s \to \mu \nu_\mu, \tag{14}$$

$$f_{D_s^+} = 309 \pm 58 \pm 33 \pm 38 \ \text{MeV from } D_s \to \tau \nu_\tau. \tag{15}$$

Recently, a rather interesting value appeared in Ref. [15]:

$$f_{D_s^+} = 323 \pm 44 \pm 12 \pm 34 \ \text{MeV from } D_s \to \mu \nu_\mu, \tag{16}$$

which is obtained by measuring the branching fraction of $D_s \to \mu\nu_\mu$ relative to the branching fraction $D_s \to \varphi\pi \to K^+K^-\pi$. We use the statistical average of the above three:

$$f_{D_s} = 252 \pm 31 \ \text{MeV}. \tag{17}$$

Then we get the theoretical predictions

$$\begin{aligned}
\mathcal{R}_{D_s/\pi} &= [3.38 \pm 0.841] \\
&\times \left| \frac{\tilde{a}(DD_s)}{\tilde{a}(D\pi)} \right|^2 \left(\frac{f_{D_s}}{0.252} \right)^2 \left(\frac{F_0^{BD}(m_{D_s}^2)}{0.74} \right)^2 \left(\frac{0.686}{F_0^{BD}(m_\pi^2)} \right)^2, \\
\mathcal{R}_{D_s^*/\rho} &= [0.92 \pm 0.236] \\
&\times \left| \frac{\tilde{a}(DD_s^*)}{\tilde{a}(D\rho)} \right|^2 \left(\frac{f_{D_s^*}}{0.252} \right)^2 \left(\frac{F_1^{BD}(m_{D_s^*}^2)}{0.817} \right)^2 \left(\frac{0.701}{F_1^{BD}(m_\rho^2)} \right)^2, \\
\tilde{\mathcal{R}}_{D_s/\pi} &= [2.17 \pm 0.654] \\
&\times \left| \frac{\tilde{a}(D^*D_s)}{\tilde{a}(D^*\pi)} \right|^2 \left(\frac{f_{D_s}}{0.252} \right)^2 \left(\frac{A_0^{BD^*}(m_{D_s}^2)}{0.793} \right)^2 \left(\frac{0.699}{A_0^{BD^*}(m_\pi^2)} \right)^2, \\
\tilde{\mathcal{R}}_{D_s^*/\rho} &= [2.15 \pm 0.545] \\
&\times \left| \frac{\tilde{a}(D^*D_s^*)}{\tilde{a}(D^*\rho)} \right|^2 \left(\frac{f_{D_s^*}}{0.252} \right)^2 \left(\frac{A_1^{BD^*}(m_{D_s^*}^2)}{0.730} \right)^2 \left(\frac{0.673}{A_1^{BD^*}(m_\rho^2)} \right)^2,
\end{aligned} \tag{18}$$

where the quoted errors are based on our estimates of uncertainties in the form-factor model dependence and in the decay constants $f_{D_s^{(*)}}$. Here we assumed $f_{D_s^*} = f_{D_s}$ for simplicity and used $f_\pi = 131$ MeV and $f_\rho = 209$ MeV [7]. As the ratios of $\tilde{a}$'s are factored out, the numerical predictions of Eqs. (18) correspond to those in the naive factorization approximation. As is shown, the main uncertainty comes from our ignorance of the decay constant $f_{D_s^{(*)}}$. Within the generalized factorization (GF) scheme and by including penguin effects, the central values of the ratios are shifted to

$$\begin{aligned}
\mathcal{R}^{\text{GF}}_{D_s/\pi} &= 2.43 \pm 0.61, \quad \mathcal{R}^{\text{GF}}_{D_s^*/\rho} = 0.85 \pm 0.22, \\
\tilde{\mathcal{R}}^{\text{GF}}_{D_s/\pi} &= 2.33 \pm 0.70, \quad \tilde{\mathcal{R}}^{\text{GF}}_{D_s^*/\rho} = 2.00 \pm 0.50,
\end{aligned} \tag{19}$$

where we used the explicit numerical values for $\tilde{a}$ of Eq. (3). Considering the current experimental branching ratios for each decay mode [10,14], one gets the following ratios:

$$\begin{aligned}
\mathcal{R}^{\text{exp}}_{D_s/\pi} &= 2.67 \pm 1.061, \quad \mathcal{R}^{\text{exp}}_{D_s^*/\rho} = 1.27 \pm 0.671, \\
\tilde{\mathcal{R}}^{\text{exp}}_{D_s/\pi} &= 3.58 \pm 1.138, \quad \tilde{\mathcal{R}}^{\text{exp}}_{D_s^*/\rho} = 2.16 \pm 0.817.
\end{aligned} \tag{20}$$

Comparing the ratios (18), (19), and (20), all the theoretical predictions are well within the present experimental constraints. We note that the inclusion of the penquin effects for $\overline{B^0} \to D_s^- D^+$, which add a sizable contribution, improves the central value so that it is much closer to the experimental value.

Although presently the experimental errors are too large to say anything definite, our analysis indicates that the factorization hypothesis is still a good method for describing the B meson decaying to heavy-heavy mesons. Furthermore, one could even consider the possibility that the factorization may not be a consequence of only perturbative QCD, in contrast to the arguments of Ref. [7]. Similar arguments are given in Ref. [16], in which the authors considered $B \to D^{(*)}X$ decays and expected nonfactorization effects would grow with the invariant mass m_X^2 of the multihadronic state X if the factorization is a consequence of perturbative QCD, but they found no such dependence on m_X^2.

A comparison of Eqs. (19) and (20) will give a test of the generalized factorization model that we considered in this paper. As it stands now, the two sets of values are consistent well within uncertainties. On the theoretical side, the biggest uncertainty is in the determination of meson decay constants $f_{D_s^{(*)}}$, while on the experimental side the statistical errors of $\mathcal{B}(B \to D^{(*)}D_s^{(*)})$ give the largest uncertainty. Therefore, we need to improve the precision of such experimental measurements for the method described in this paper to have any significance [17].

Currently, the most precise measurement of f_{D_s} is obtained by the CLEO Collaboration [18] in $D_s \to \mu\nu$ decays. Adding the errors in quadrature, they obtained $f_{D_s} = 280 \pm 48$; 17% total uncertainty (7% statistical) in f_{D_s}, corresponding to 34% error in our calculation of the ratios. With the 100 fb^{-1} data sample from BaBar and Belle, which is more than 20 times that of the existing result [18], the statistical error will be reduced to $1/\sqrt{20}$ of Ref. [18]. The systematic errors may not go down as fast, but a better understanding of every other aspect of the analysis will help reduce the systematic uncertainties. Assuming that the systematic error can be reduced to $\frac{1}{3}$ of Ref. [18], the f_{D_s} value will be determined to 5% accuracy, hence resulting in 10% error in our ratio. As for the form-factor errors in the theoretical calculations, we hope that in the near future precision measurements in heavy-flavor physics processes from B or charm factories will help test and confirm the reliability of the lattice QCD technique. Then we may have much fewer form-factor errors.

In the experimental measurements of branching ratios, $B \to D^{(*)}\pi$ modes are measured with much better precision than $B \to D^{(*)}\rho$ modes. Similarly, $D^{(*)}D_s$ modes are determined with significantly higher precision than $D^{(*)}D_s^*$ modes. Therefore, we expect that $R_{D_s/\pi}$ and $\tilde{R}_{D_s/\pi}$ will be determined with higher precision than other ratios.

Comparing Eqs. (19) and (20), we note that the experimental and theoretical values of $\tilde{R}_{D_s/\pi}$ show the biggest difference if we accept their central values. We also note that if both values can be determined within 10% accuracy and if we assume that their central values stand as they are, then we will be able to see a 3σ difference in $\tilde{R}_{D_s/\pi}$. In conclusion, we will have a good opportunity to test the generalized factorization scheme as discussed in this paper once we have $\sim 100\ \mathrm{fb}^{-1}$ of data from the B-factory experiments.

To summarize, we have investigated the possibility of testing the factorization hypothesis from nonleptonic exclusive decays of a B meson into two meson final states. In particular, we considered the *presumably* nonfactorizable $\overline{B}^0 \to D^{(*)+}D_s^{(*)-}$ modes and $\overline{B}^0 \to D^{(*)+}(\pi^-,\rho^-)$ known as well-factorizable modes. By taking the ratios $\mathcal{B}(\overline{B}^0 \to D^{(*)+}D_s^{(*)-})/\mathcal{B}[\overline{B}^0 \to D^{(*)+}(\pi^-,\rho^-)]$, the dependence on CKM matrix elements vanishes and some model dependence on hadronic form factors is reduced. We found that under the present theoretical and experimental uncertainties, there is no evidence of a breakdown of the factorization description to heavy-heavy decays of the B meson.

We thank G. Cvetic for a careful reading of the manuscript and his valuable comments. The work of C.S.K. was supported in part by CHEP-SRC Program, Grant No. 20015-111-02-2 and Grant No. R03-2001-00010 of the KOSEF, in part by BK21 Program. The work of Y.K. was supported by the 2000 Yonsei University Faculty Research Fund. The work of J.L. was supported by a KRF Grant, Project No. 2001-042-D00022. The work of W.N. was supported by the Research Program of Dongguk University.

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