$B \to \phi K$ and $B \to \phi X_s$ in the heavy quark limit

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(Received 20 November 2000; published 29 March 2001)

We study $B \to \phi K$ and $B \to \phi X_s$ decays in the heavy quark limit using perturbative QCD. The next leading order corrections introduce substantial modifications to the naive factorization results (more than 50%). The branching ratio $Br(B \to \phi K)$ is predicted to be in the range $[F_1^{B\to K}(m_\phi^2)/0.33]^2(3.2-4.5)\times 10^{-6}$ that is within the one σ allowed region from the central value of 6.2×10^{-6} measured by CLEO Collaboration, but outside the one σ allowed region from the central value of 17.2×10^{-6} measured by BELLE Collaboration for reasonable $F_1^{B\to K}$. For the semi-inclusive decay $B \to \phi X_s$ we also include initial bound state effects in the heavy quark limit that decreases the branching ratio by about 10%. $Br(B\to \phi X_s)$ is predicted to be in the range $(4.8-6.6)\times 10^{-5}$.

DOI: 10.1103/PhysRevD.63.094004 PACS number(s): 13.25.Hw, 12.38.Bx

Recently CLEO and BELLE have measured the penguin-induced $\Delta S=1$ hadronic B decays with $Br(B^- \to \phi K) =(6.4^{+2.5+0.5}_{-2.1-2.0}\times 10^{-6})$, $Br(\bar{B}^0 \to \phi \bar{K}^0)=(5.9^{+4.0+1.1}_{-2.9-0.9}\times 10^{-6})$ from CLEO [1], and $Br(B^- \to \phi K^-)=(1.72^{+0.67+0.18}_{-0.54-0.18}\times 10^{-5})$ from BELLE Collaboration [2]. Although the central values do not agree with each other, they are consistent at the 2σ level. The branching ratios will soon be determined with better precisions at CLEO, BABAR, and BELLE Collaborations. These decay modes are particularly interesting in the standard model, as they are purely due to penguin amplitudes to leading order [3,4] and therefore are sensitive to new physics at the loop level [5]. The neutral decay mode also provides a model independent measurement for one of the Kobayashi-Maskawa (KM) unitarity triangle parameters $\sin 2\beta$. The related semi-inclusive decay mode $B\to\phi X_s$ is also purely due to penguin amplitude [3,6] and is sensitive to new physics at the loop level. The branching ratio for this decay, although not measured at present, will be measured in the near future at B factories. The above exclusive and semi-inclusive decays have been studied theoretically before with large errors [3,4,6] that both the CLEO and BELLE measurements can be accommodated.

Previous calculations for the branching ratios $Br(B \to \phi K)$ and $Br(B\to\phi X_s)$ are based on naive factorization calculations. In these calculations, nonfactorization effects cannot be calculated and are usually parametrized by an effective color number that is treated as a free parameter. There are also uncertainties related to gluon virtuality in the penguin diagrams and the dependence of the renormalization scale. To have a better understanding of these decays, it is necessary to carry out calculations in such a way that the problems mentioned and other potential problems can be dealt with. It has recently been shown that it is indeed possible in the heavy quark limit to handle most of the problems mentioned in relation to B to two light mesons from QCD calculations [7,8]. Several decays have been studied with interesting results [9,10]. In this paper we will follow the method developed in Ref. [8] to carry out calculations for the branching ratios for $B\to\phi K$ and $B\to\phi X_s$.

The effective Hamiltonian for charmless B decays with $\Delta S=1$ is given by

$$H_{eff}=\frac{G_F}{\sqrt{2}}\left\{V_{ub}V_{us}^*\left(c_1O_1+c_2O_2+\sum_{i=3}^{11}c_iO_i\right)+V_{cb}V_{cs}^*\sum_{i=3}^{11}c_iO_i\right\}. \tag{1}$$

Here O_i are quark and gluon operators and are given by

$$O_1=(\bar{s}_\alpha u_\beta)_{V-A}(\bar{u}_\beta b_\alpha)_{V-A}, \tag{2}$$

$$O_2=(\bar{s}_\alpha u_\alpha)_{V-A}(\bar{u}_\beta b_\beta)_{V-A},$$

$$O_{3(5)}=(\bar{s}_\alpha b_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\beta q'_\beta)_{V-(+)A},$$

$$O_{4(6)}=(\bar{s}_\alpha b_\beta)_{V-A}\sum_{q'}(\bar{q}'_\beta q'_\alpha)_{V-(+)A},$$

$$O_{7(9)}=\frac{3}{2}(\bar{s}_\alpha b_\alpha)_{V-A}\sum_{q'}e_{q'}(\bar{q}'_\beta q'_\beta)_{V+(-)A},$$

$$O_{8(10)}=\frac{3}{2}(\bar{s}_\alpha b_\beta)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\beta q'_\alpha)_{V+(-)A},$$

$$O_{11}=\frac{g_s}{8\pi^2}m_b\bar{s}_\alpha\sigma^{\mu\nu}G^a_{\mu\nu}\frac{\lambda_a^{\alpha\beta}}{2}(1+\gamma_5)b_\beta,$$

where $(V\pm A)(V\pm A)=\gamma^\mu(1\pm\gamma_5)\gamma_\mu(1\pm\gamma_5)$, $q'=u,d,s,c,b$, $e_{q'}$ is the electric charge number of q' quark, λ_a is the color SU(3) Gell-Mann matrix, α and β are color indices, and $G_{\mu\nu}$ is the gluon field strength.

The coefficients c_i are the Wilson coefficients that have been calculated in different schemes [3,11]. In this paper we will use, consistently, the naive dimensional reduction (NDR) scheme. The values of c_i at $\mu\approx m_b$ GeV with the next-to-leading order (NLO) QCD corrections are given by [11]

$$c_1=-0.185,\quad c_2=1.082,\quad c_3=0.014,$$

$$c_4=-0.035,\quad c_5=0.009,\quad c_6=-0.041,$$

$$c_7=-0.002\alpha_{em},\quad c_8=0.054\alpha_{em},\quad c_9=-1.292\alpha_{em},$$

$$c_{10}=-0.263\alpha_{em},\quad c_{11}=-0.143.$$

Here $\alpha_{em}=1/137$ is the electromagnetic fine structure constant.

The exclusive $B\to\phi K$ decay

In decay, amplitude can be expanded according to the two small numbers α_s and Λ_{QCD}/m_b in the problem. In the heavy b quark limit, the decay amplitude due to a particular operator can be represented in the form [8]

$$\langle\phi K|O|B\rangle=\langle\phi K|O|B\rangle_{fact}\times\left[1+\sum r_n\alpha_s^n+O(\Lambda_{QCD}/m_b)\right],\qquad(3)$$

where $\langle\phi K|O|B\rangle_{fact}$ indicates the naive factorization result. The parameter $\Lambda_{QCD}\approx0.3$ GeV is the strong interaction scale. The second and third terms in the square brackets indicate higher order α_s and Λ_{QCD}/m_b corrections to the matrix elements. Including the next-leading order corrections and using information from Ref. [10], we have the decay amplitude for $B\to\phi K$ in the heavy-quark limit as,

$$A(B\to\phi K)=\frac{G_F}{\sqrt{2}}C\langle\phi|\bar{s}\gamma_\mu s|0\rangle\langle K|\bar{s}\gamma^\mu b|B\rangle,$$

$$C=V_{ub}V_{us}^*[a_3^u+a_4^u+a_5^u-\tfrac{1}{2}(a_7^u+a_9^u+a_{10}^u)+a_{10a}^u]$$

$$V_{cb}V_{cs}^*[a_3^c+a_4^c+a_5^c-\tfrac{1}{2}(a_7^c+a_9^c+a_{10}^c)+a_{10a}^c)].\qquad(4)$$

We will use the notation

$$\langle\phi|\bar{s}\gamma_\mu b|0\rangle=m_\phi f_\phi\epsilon_\mu^\phi$$

and

$$\langle K|\bar{s}\gamma^\mu b|B\rangle=F_1^{B\to K}(q^2)(p_B^\mu+p_K^\mu)+[F_0^{B\to K}(q^2)-F_1^{B\to K}(q^2)](m_B^2-m_K^2)q^\mu/q^2.$$

The coefficients $a_i^{u,c}$ are given by

$$a_3^u=a_3^c=c_3+\frac{c_4}{N}+\frac{\alpha_s}{4\pi}\frac{C_F}{N}c_4F_\phi,$$

$$a_4^p=c_4+\frac{c_3}{N}+\frac{\alpha_s}{4\pi}\frac{C_F}{N}\left\{c_3[F_\phi+G_\phi(s_s)+G_\phi(s_b)]+c_1G_\phi(s_p)+(c_4+c_6)\sum_{f=u}^{b}G_\phi(s_f)+c_{11}G_{\phi,11}\right\},$$

$$a_5^u=a_5^c=c_5+\frac{c_6}{N}+\frac{\alpha_s}{4\pi}\frac{C_F}{N}c_6(-F_\phi-12),$$

$$a_7^u=a_7^c=c_7+\frac{c_8}{N}+\frac{\alpha_s}{4\pi}\frac{C_F}{N}c_8(-F_\phi-12),$$

$$a_9^u=a_9^c=c_9+\frac{c_{10}}{N}+\frac{\alpha_s}{4\pi}\frac{C_F}{N}c_{10}F_\phi,$$

$$a_{10}^u=a_{10}^c=c_{10}+\frac{c_9}{N}+\frac{\alpha_s}{4\pi}\frac{C_F}{N}c_9F_\phi,$$

$$a_{10a}^p=\frac{\alpha_s}{4\pi}\frac{C_F}{N}\left\{(c_8+c_{10})\frac{3}{2}\sum_{f=u}^{b}e_fG_\phi(s_f)+c_9\frac{3}{2}[e_sG_\phi(s_s)+e_bG_\phi(s_b)]\right\},\qquad(5)$$

where p takes the values u and c, $N=3$ is the number of color, $C_F=(N^2-1)/2N$, and $s_f=m_f^2/m_b^2$. The other items are given by

$$G_\phi(s)=\frac{2}{3}-\frac{4}{3}\ln\frac{\mu}{m_b}+4\int_0^1dx\,\phi_\phi(x)\times\int_0^1du\,u(1-u)\ln[s-u(1-u)(1-x)],\qquad(6)$$

$$G_{\phi,11}=-\int_0^1dx\frac{2}{1-x}\phi_\phi(x),$$

$$F_\phi=-12\ln\frac{\mu}{m_b}-18+f^I_\phi+f^{II}_\phi,$$

$$f^I_\phi=\int_0^1 dx\, g(x)\phi_\phi(x),$$

$$g(x)=3\frac{1-2x}{1-x}\ln x-3i\pi,$$

$$f^{II}_\phi=\frac{4\pi^2}{N}\frac{f_K f_B}{F_1^{B\to K}(0)m_B^2}\int_0^1 dz\frac{\phi_B(z)}{z}\times\int_0^1 dx\frac{\phi_K(x)}{x}\int_0^1 dy\frac{\phi_\phi(y)}{y}.$$

Here $\phi_i(x)$ are meson wave functions. In this paper we will take the following forms for them [9]:

$$\phi_B(x)=N_B x^2(1-x)^2\exp\left[-\frac{m_B^2x^2}{2\omega_B^2}\right],$$

$$\phi_{K,\phi}(x)=6x(1-x), \tag{7}$$

where N_B is a normalization factor satisfying $\int_0^1 dx\,\phi_B(x)=1$. Fitting various B decay data, ω_B is determined to be 0.4 GeV.

The above results are from genuine leading QCD calculation in the heavy quark limit. The number of color should not be treated as an effective number, but has to be three from QCD. The results are renormalization scale independent. The problem associated with the gluon virtuality $k^2=(1-x)m_B^2$ in the naive factorization calculation is also meaningfully treated by convoluting the x dependence with the meson wave functions in the functions $G(s,x)$. Also leading nonfactorizable is included (by the term proportional to f^{II}_ϕ). There are still uncertainties in the calculation, such as the form of the wave functions and the unknown $B\to K$ transition form factor $F_1^{B\to K}(q^2)$. However using wave functions obtained by fitting other data, the errors can be reduced. In any case calculations based on the method used here is on more solid ground compared with previous calculations.

The decay rate can be easily obtained and is given by

$$\Gamma(B\to\phi K)=\frac{G_F^2}{32\pi}|C|^2 f_\phi^2 F_1^{B\to K}(m_\phi^2)^2 m_B^3\lambda_{K\phi}^{3/2}, \tag{8}$$

where $\lambda_{ij}=(1-m_i^2/m_B^2-m_j^2/m_B^2)^2-4m_i^2m_j^2/m_B^4$.

In our numerical calculations we will use the following values for the relevant parameters [12]: $m_b=4.8$ GeV, $m_c=1.4$ GeV, $V_{us}=0.2196$, $V_{cb}=0.0395$, $V_{ub}/V_{cb}=0.085$, $f_\phi=0.233$ GeV, $f_K=0.158$ GeV, and $f_B=(180\pm20)$ MeV. We keep the phase γ to be a free parameter. The results on the branching ratios are not sensitive to light quark masses. We obtain the branching ratios for $B\to\phi K$ to be

$$Br(B^-\to\phi K^-)=\left(\frac{F_1^{B\to K}(m_\phi^2)}{0.33}\right)^2(3.8-4.1)\times10^{-6},$$

$$Br(\overline{B^0}\to\phi\overline{K^0})=\left(\frac{F_1^{B\to K(m_\phi^2)}}{0.33}\right)^2(3.6-3.9)\times10^{-6}. \tag{9}$$

We have checked sensitivities on some of the parameters. The branching ratios are insensitive to the phase angle γ because terms proportional to $e^{-i\gamma}$ are suppressed by $|V_{ub}V_{us}^*/V_{cb}V_{cs}^*|$ which is about 1/50. The error on V_{cb} is about 5% that leads to an uncertainty of about 10% for the branching ratios. Including this uncertainty, the branching ratios are given in the range of $(3.4-4.5)\times10^{-6}$ and $(3.2-4.3)\times10^{-6}$ for $B^-\to K^-\phi$ and $\overline{B^0}\to\overline{K^0}\phi$, respectively. We find that the NLO corrections to the matrix elements (terms proportional to α_s in a_i) to be significant. Without such NLO corrections, the branching ratios are in the range of $[F_1^{B\to K}(m_\phi^2)/0.33]^2(2.1-2.8)\times10^{-6}$. The nonfactorizable contributions (terms proportional to f^{II}_ϕ) tend to reduce the branching ratios at a few percent level. The form factor $F_1^{B\to K}$ is the least-known parameter in the calculations. There are several calculations for this parameter. Lattice calculation gives 0.27 ± 0.11 [13], Bauer-Stech-Wirdel (BSW) model gives 0.38 [14], while light-cone calculation gives 0.35 ± 0.05 [15]. Using the average central value from these calculations, $F_1^{B\to K}(0)=0.33$, one finds that the predicted branching ratios are closer to the averaged central value of the measurements from CLEO than that from BELLE. To reach the CLEO central values, $F_1^{B\to K}$ needs to be around 0.42 that is on the high value side from theoretical calculations, while to reach BELLE central value an unreasonably large value 0.72 for $F_1^{B\to K}$ is needed. Precise measurements of these modes may provide a good measurement of the form factor $F_1^{B\to K}$. If a better understanding of the form factor $F_1^{B\to K}$ can be obtained from other experimental measurements and from theoretical calculations in the future, precise measurement of $B\to\phi K$ may provide us with important information about new physics beyond the SM.

The semi-inclusive $B\to\phi X_s$ decay

We will follow the procedures for semi-inclusive B decays described in Ref. [16] to study $B\to\phi X_s$. The final state X_s can be divided into two parts, $X_s=X_s'+X$. Here X_s' can be viewed as containing a perturbatively produced s quark and some nonperturbatively produced state nonstrange state that are not related to the s and $\bar{s}$ forming the ϕ. X is the nonperturbatively produced state containing no strange number but associated with the s and $\bar{s}$ forming the ϕ. Neglecting color octet contribution and summing over all X_s', the decay width for each of the helicity state λ of $\phi(\lambda)$, at the leading order with light quark masses set to zero, can be written as

$$\Gamma_\lambda(B\to\phi X_s)=\frac{1}{2}G_F^2|\tilde{C}|^2\int\frac{d^3k}{(2\pi)^3}\frac{d^4q}{(2\pi)^4}2\pi\delta(q^2)\int d^4x\, e^{iq\cdot x}\cdot\langle B|\bar{b}\gamma_\mu(1-\gamma_5)\gamma\cdot q\,\gamma_\nu(1-\gamma_5)$$
$$\times b(x)|B\rangle\cdot\sum_X\langle 0|\overline{s(0)}\gamma^\mu(1-\gamma_5)s(0)|\phi(\lambda)+X\rangle\langle\phi(\lambda)+X|\overline{s(x)}\gamma^\nu(1-\gamma_5)s(x)|0\rangle, \tag{10}$$

where the parameter $\tilde{C}$ is related to the Wilson coefficients c_i. In the vacuum-saturation approximation,

$$\sum_X\langle 0|\overline{s(0)}\gamma^\mu(1-\gamma_5)s(0)|\phi(\lambda)+X\rangle$$
$$\times\langle\phi(\lambda)+X|\overline{s(x)}\gamma^\nu(1-\gamma_5)s(x)|0\rangle$$
$$\approx\langle 0|\overline{s(0)}\gamma^\mu(1-\gamma_5)s(0)|\phi(\lambda)\rangle$$
$$\times\langle\phi(\lambda)|\overline{s(x)}\gamma^\nu(1-\gamma_5)s(x)|0\rangle. \tag{11}$$

In this approximation the color octet contributions are automatically neglected. We will work with this approximation to estimate the branching ratio for $B\to\phi X_s$. This approximation is consistent with the assumption made in the previous section if color octet is neglected. If one cuts the ϕ momentum to be above 2 GeV or so, the contributions are dominated by the effective two-body decay $b\to\phi s$. In this case $\tilde{C}$ is similar to C but with f_ϕ^{II} set to be zero. In principle, terms proportional to f_ϕ^{II} also contribute. However this contribution is small and can be neglected. This is because that in the semi-inclusive decay only ϕ in the final state is specified. When the constraint of having K in the final state is relaxed, the term corresponding to f_ϕ^{II} leads to a three-body decay. Requiring the identified hadron in the final state to be hard limits the phase space [16] and results in a small contribution from f_ϕ^{II} compared with other contributions.

If the b quark mass is infinitively large, $Br(B\to\phi X_s)$ is equal to $Br(b\to\phi s)$. However due to the initial b quark bound state effect there are corrections [17]. This correction is included in the factor $\langle B|\overline{b(0)}\gamma_\mu(1-\gamma_5)\gamma\cdot q\gamma^\nu(1-\gamma_5)b(x)|B\rangle$. Following the discussions in Ref. [17] we obtain the $1/m_b^2$ correction factor,

$$\Gamma(B\to\phi X_s)\approx\frac{G_F^2f_\phi^2m_b^3}{16\pi}|\tilde{C}|^2\left(1+\frac{7}{6}\frac{\mu_g^2}{m_b^2}-\frac{53}{6}\frac{\mu_\pi^2}{m_b^2}\right), \tag{12}$$

where

$$\mu_g^2=\langle B|\bar{h}\frac{1}{2}g_sG_{\mu\nu}\sigma^{\mu\nu}h|B\rangle,$$
$$\mu_\pi^2=-\langle B|\bar{h}D_T^2h|B\rangle. \tag{13}$$

Here the field h is related to b by

$$b(x)=e^{-im_bv\cdot x}\{1+i\gamma\cdot D_T/2m_b+v\cdot D\gamma\cdot D_T/4m_b^2$$
$$-(\gamma\cdot D_T)^2/8m_b^2\}h(x)+O(1/m_b^3)$$
$$+(\text{terms for antiquark}).$$

$D_T^\mu=D^\mu-v^\mu v\cdot D$ with v being the four velocity of the B meson satisfying $v^2=1$ and $D^\mu=\partial^\mu+ig_sG^\mu(x)$.

Analysis of spectroscopy of heavy hadrons and QCD sum rule calculations give [18] $\mu_g^2\approx 0.36\ \mathrm{GeV}^2$ and $\mu_\pi^2\approx(0.3-0.54)\ \mathrm{GeV}^2$. We will use $\mu_g^2=\mu_\pi^2=0.36\ \mathrm{GeV}^2$ for numerical calculations. The initial state $1/m_b^2$ correction reduces the branching ratio by about 10%. The branching ratio for $B\to\phi X_s$ is predicted to be

$$Br(B\to\phi X_s)=(5.3-6.0)\times 10^{-5}. \tag{14}$$

This prediction, as in the case for exclusive decays, is insensitive to the phase angle γ. The NLO corrections enhance the branching ratio significantly, similar to the exclusive decay cases.

The expression for the semi-inclusive decay in Eq. (12), on the face of it, has fewer parameters (no dependence on $F_1^{B\to K}$) compared with the exclusive branching ratios discussed earlier. One might think that the prediction for $Br(B\to\phi X_s)$ is more certain compared with the exclusive cases. However, one should be careful about this because in the calculation we have only included color singlet and the $^3S_1\ s\bar{s}$ bound state contribution. There may be other contributions such as color octet and other S and P wave states from $s\bar{s}$. These contributions are in general smaller than the contributions already considered. One cannot rule out significant enhancement at present. However, we can view the color singlet result as a leading contribution that gives a good order of magnitude estimate of the semi-inclusive decay $B\to\phi X_s$.

In conclusion, we have studied $B\to\phi K$ and $B\to\phi X_s$ decays in the heavy quark limit using perturbative QCD. We found that the next leading order corrections introduce substantial modifications to the leading native factorization results (more than 50%). The branching ratio $Br(B\to\phi K)$ is predicted to be in the range $[F_1^{B\to K}(m_\phi^2)/0.33]^2(3.2-4.5)\times 10^{-6}$ which is within the one σ allowed region from the central value of 6.2×10^{-6} measured by CLEO, but outside the one σ allowed region from the central value of 17.2×10^{-6} measured by BELLE for reasonable $F_1^{B\to K}$. For the semi-inclusive decay $B\to\phi X_s$ we also included initial bound state effect in the heavy quark limit that decreases the branching ratio by about 10%. $Br(B \to \phi X_s)$ is predicted to be in the range $(5.3-6.0)\times 10^{-5}$. Future experimental data will provide us with more information about these decays and about the method based on QCD improved factorization approximation.

This work was supported in part by NSC under Grant No. NSC 89-2112-M-002-016 and the NCTS.

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