Contribution of the J/ψ resonance to the radiative B decays

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The radiative decays of the B mesons may have a significant contribution from the transition $b \to sJ/\psi$ followed by the J/ψ-photon conversion. The size of this contribution is reanalyzed in the light of a phenomenological model for the weak bsJ/ψ vertex, and a modified J/ψ-photon interaction that is manifestly gauge invariant. Predictions for both inclusive and exclusive cases are obtained, but large uncertainties still remain.

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I. INTRODUCTION

The CLEO Collaboration has observed the exclusive radiative decays of charged and neutral B mesons into K^* [1], with an average branching ratio

$$B(B \to K^*\gamma) = (4.5 \pm 1.5 \pm 0.9) \times 10^{-5}. \quad (1)$$

More recently, the same experiment reported the first signs of the inclusive decay $B \to \gamma + X_s$ [2], with the branching ratio

$$B(B \to \gamma + X_s) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}. \quad (2)$$

At the origin of these decays is predominantly the spectator process involving the $bs\gamma$ vertex. In the standard model, the short distance contribution to the vertex occurs at the one-loop level, but it is sizable due to the large top-quark mass and an important QCD enhancement [3]. It can be calculated perturbatively, and the QCD corrections have been included in the leading logarithm approximation [4]. The uncertainty in this result is mostly due to the choice of the scale at which to calculate the QCD corrections; with the full next-to-leading order calculation completed, this error should be substantially smaller [5]. However, it is possible that a significant long distance contribution to the $bs\gamma$ vertex exists, due to the process $b \to sJ/\psi \to s\gamma$. The weak decay of the b quark that produces the J/ψ meson occurs at the tree level; the J/ψ in turn couples to the photon, as in the $J/\psi \to e^+e^-$ decay mode. For the inclusive decay, a naive estimate gives

$$|A(b \overset{J/\psi}{\to} s\gamma)| \sim |A(b \to sJ/\psi)|\, e g_{J/\psi\gamma} \frac{1}{m^2_{J/\psi}}, \quad (3)$$

for the J/ψ contribution to the decay amplitude. The strength of the J/ψ-photon conversion, $g_{J/\psi\gamma} = 0.82$ GeV^2, is measured from the rate for $J/\psi \to e^+e^-$. Equation (3) gives a long distance contribution that is about 20% of the observed $b \to s\gamma$ amplitude. The analogous estimate for the exclusive decay $B \to K^*\gamma$ gives a J/ψ contribution in the same proportion. This effect was first pointed out by Golowich and Pakvasa [6] as the dominant long distance contribution to the radiative B decays; a phenomenological model for the exclusive process $B \overset{J/\psi}{\to} K^*\gamma$ was proposed in Ref. [6], and later expanded in Ref. [7] (the analogous effect in the $B \to \rho\gamma$ decay was discussed recently by Cheng [8]). The inclusive case was considered by Deshpande, Trampetic, and Panose in Ref. [9], where a model could not be found that would satisfy gauge invariance and give a nonzero result. More recently, one such model was suggested by Deshpande, He, and Trampetic [10].

In this work, the mechanism behind the long distance contribution of the J/ψ to the B-meson radiative decays is reanalyzed, within a new phenomenological approach. The analysis will be based on an effective bsJ/ψ vertex (Sec. II A), parametrized by form factors that are to be determined empirically, and a J/ψ-photon interaction (Sec. II B), modeled after vector meson dominance (VMD) ideas [11]. From this description one derives both the amplitude for the inclusive process $b \to sJ/\psi \to s\gamma$ and that for the exclusive process $B \to K^*J/\psi \to K^*\gamma$ (Sec. II C). These amplitudes are automatically gauge invariant, and vanish when the bsJ/ψ vertex is calculated in the factorization approximation. Quantitative predictions are derived (Sec. III), but significant uncertainties still remain. This work was inspired by the recent analysis of Ref. [7], which also adopts a phenomenological approach to determine the size of the long distance effect, for the case of the exclusive decay. The model and the results obtained in here are, however, substantially different. The same is true with respect to the other analyses that have appeared in the literature [12].

II. J/ψ CONTRIBUTION TO THE RADIATIVE B DECAYS

A. bsJ/ψ vertex

The amplitude for the inclusive decay $b \to sJ/\psi$ is given by

$$A(b \to sJ/\psi) = -\langle sJ/\psi|H_{\text{eff}}|b\rangle, \quad (4)$$

where H_{eff} is the effective Hamiltonian that describes the weak process $b \to sc\bar{c}$:

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}}\, V_{cb}V_{cs}^{*}\,(C_1\,\bar{c}_\alpha\gamma_\mu L c_\beta\,\bar{s}_\beta\gamma^\mu L b_\alpha + C_2\,\bar{c}_\alpha\gamma_\mu L c_\alpha\,\bar{s}_\beta\gamma^\mu L b_\beta) \qquad (5)$$

$(L, R \equiv 1 \mp \gamma_5)$. The Wilson coefficients C_1 and C_2 contain the short distance QCD corrections. In the leading logarithm approximation, for $\Lambda^{(5)}_{\overline{\rm MS}} = 200$ MeV [13], where $\overline{\rm MS}$ denotes the modified minimal subtraction scheme, and at the scale $\mu = 5.0$ GeV, they are [14]

$$C_1 = 1.117, \qquad C_2 = -0.266. \qquad (6)$$

The soft QCD effects in the hadronization of the c-$\bar{c}$ pair are described in terms of form factors that parametrize the matrix element of $H_{\rm eff}$, in Eq. (4). For example, in the factorization prescription [15],

$$\begin{aligned}\langle sJ/\psi|\bar{c}_\alpha\gamma_\mu L c_\alpha\,\bar{s}_\beta\gamma^\mu L b_\beta|b\rangle &= 3\langle sJ/\psi|\bar{c}_\alpha\gamma_\mu L c_\beta\,\bar{s}_\beta\gamma^\mu L b_\alpha|b\rangle \\ &= m_{J/\psi} f_{J/\psi}\varepsilon^*_\mu \overline{u}_s\gamma^\mu L u_b.\end{aligned} \qquad (7)$$

The J/ψ decay constant $f_{J/\psi}$ is defined by $\langle 0|\bar{c}\gamma_\mu c|J/\psi\rangle = m_{J/\psi} f_{J/\psi}\varepsilon_\mu$, and it is the only form factor that enters the $b \to sJ/\psi$ decay amplitude, within factorization. From $\Gamma(J/\psi \to e^+e^-) = (5.26 \pm 0.37)$ keV [13], it follows that $f_{J/\psi} = 395$ MeV.

In all generality, however, one can write an effective bsJ/ψ vertex that, for on-shell quarks and with $m_s = 0$, is given by

$$\Lambda^\mu_{bsJ/\psi} = -\frac{G_F}{\sqrt{2}}\, V_{cb}V_{cs}^{*}\,(C_2 + \tfrac{1}{3}C_1)\,[g_0(k^2)\,k^\mu\, \not{k} L + g_1(k^2)\,(k^2 g^{\mu\nu} - k^\mu k^\nu)\gamma_\nu L + g_2(k^2)\,m_b i\sigma^{\mu\nu}k_\nu R], \qquad (8)$$

where k is the J/ψ four-momentum. The motivation to adopt this more general approach is the fact that the factorization result $g_1(m^2_{J/\psi}) = g_0(m^2_{J/\psi}) = f_{J/\psi}/m_{J/\psi}$ and $g_2(m^2_{J/\psi}) = 0$ gives a very poor agreement with the data, for both the inclusive and the exclusive decays [15]. Indeed, at present, there is no satisfactory theoretical description of the weak b decay that produces the J/ψ meson. In here, the form factors g_1 and g_2, at $k^2 = m^2_{J/\psi}$, are to be determined empirically from the data for the B-meson decays into J/ψ. The term proportional to the form factor g_0 does not contribute to the decay amplitudes, and so $g_0(m^2_{J/\psi})$ will be left undetermined. Notice that, unless this form factor vanishes, the J/ψ meson couples to a current

$$J^\mu = -\bar{s}\Lambda^\mu_{bsJ/\psi} b \qquad (9)$$

that is not conserved.

B. J/ψ contribution to the $bs\gamma$ vertex

The effective $bs\gamma$ vertex, for on-shell quarks and with $m_s = 0$, is analogous to that in Eq. (8), but with an additional constraint from gauge invariance. The contribution from the c-$\bar{c}$ intermediate states is parametrized as

$$\begin{aligned}\Lambda^\mu_{bs\gamma} = -\frac{G_F}{\sqrt{2}}\, V_{cb}V_{cs}^{*}\,[&G_1^{c\bar{c}}(k^2)\,(k^2 g^{\mu\nu} - k^\mu k^\nu)\gamma_\nu L \\ &+ G_2^{c\bar{c}}(k^2)\,m_b i\sigma^{\mu\nu}k_\nu R].\end{aligned} \qquad (10)$$

The interest here is in the J/ψ contribution to the electromagnetic form factors $G^{c\bar{c}}_{1,2}$. It will be derived from the weak vertex in Eq. (8) and the photon couplings shown in Fig. 1. These couplings are modeled after the γ-ρ interaction, in the VMD description of the electromagnetic properties of the nucleons [11]. They correspond to the gauge-invariant interaction Lagrangian

$$\mathcal{L} = eQ_c\frac{f_{J/\psi}}{m_{J/\psi}}\left[-\frac{1}{2}F_{\mu\nu}\psi^{\mu\nu} - A_\mu\left(g^{\mu\nu} - \frac{\partial^\mu\partial^\nu}{\Box}\right)J_\nu\right], \qquad (11)$$

where A_μ and ψ_μ are the photon and the J/ψ fields; $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$ and $\psi_{\mu\nu} \equiv \partial_\mu\psi_\nu - \partial_\nu\psi_\mu$. The current J_ν is that in Eq. (9). The second term on the right-hand side (RHS) of Eq. (11) is an extension of the result in Ref. [11]. It encompasses the more general case where the current is not necessarily conserved: In order to preserve gauge invariance, only its conserved part was included in the interaction. The phenomenological parameter $f_{J/\psi}$ is the same as that defined before, since $J^\mu_{\rm e.m.} = Q_c\,\bar{c}\gamma^\mu c + \cdots$. In general, the two gauge-invariant terms in the interaction Lagrangian would have independent couplings. However, in the assumption of complete VMD [11], the k^2 dependence of the electromagnetic form factors is dominated by the vector meson

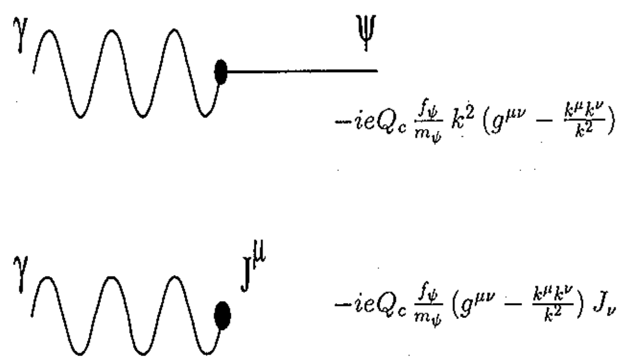

FIG. 1. The photon vertices that correspond to the interaction Lagrangian of Eq. (11).

pole, i.e., $G_{1,2}^{c\bar{c}} \propto 1/(k^2 - m_{J/\psi}^2)$; this leads to the result in Eq. (11). The J/ψ contribution to the form factors $G_{1,2}^{c\bar{c}}$, in the $bs\gamma$ vertex, is then

$$G_{1,2}^{J/\psi}(k^2) = -\left(C_2 + \tfrac{1}{3}C_1\right) eQ_c f_{J/\psi} m_{J/\psi} g_{1,2} \frac{1}{k^2 - m_{J/\psi}^2}, \tag{12}$$

where $f_{J/\psi} \times g_{1,2}$ is taken to be constant in k^2, for consistency with the complete VMD assumption. Corrections to this assumption, due to the contribution of other c-$\bar{c}$ states (such as the open charm continuum), are discussed later.

C. J/ψ contribution to the radiative decay amplitudes

The amplitudes for the inclusive and exclusive radiative B decays, due to the J/ψ contribution, follow from Eqs. (10) and (12). Only the magnetic dipole moment type structure in the vertex (i.e., the form factor $G_2^{J/\psi}$) contributes, when the photon is on-shell. For the inclusive decay, the magnitude of the J/ψ contribution is

$$\begin{aligned} |A(b \overset{J/\psi}{\to} s\gamma)| &= \left| \frac{G_F}{\sqrt{2}} V_{cb}V_{cs}^* \, G_2^{J/\psi}(0)\, m_b \, \varepsilon_{J/\psi}^{\mu *} \langle s|\bar{s} i\sigma_{\mu\nu} k^\nu R b|b\rangle \right| \\ &= \left| G_F \, V_{cb}V_{cs}^* \left(C_2 + \tfrac{1}{3}C_1\right) 2m_b^3 eQ_c \frac{f_{J/\psi}}{m_{J/\psi}} g_2 \right|, \end{aligned} \tag{13}$$

and for the exclusive $B \to K^*\gamma$ decay, it is

$$\begin{aligned} |A(B \overset{J/\psi}{\to} K^*\gamma)| &= \left| \frac{G_F}{\sqrt{2}} V_{cb}V_{cs}^* \, G_2^{J/\psi}(0)\, m_b \, \varepsilon_{J/\psi}^{\mu *} \langle K^*|\bar{s} i\sigma_{\mu\nu} k^\nu R b|B\rangle \right| \\ &= \left| \frac{G_F}{\sqrt{2}} V_{cb}V_{cs}^* \left(C_2 + \tfrac{1}{3}C_1\right) m_b eQ_c \frac{f_{J/\psi}}{m_{J/\psi}} g_2 (m_B^2 - m_{K^*}^2) F_1(0) \right|. \end{aligned} \tag{14}$$

The form factor $F_1(k^2)$ is one of the three form factors that parametrize the hadronic matrix element $\langle K^*|\bar{s}i\sigma^{\mu\nu}k_\nu Rb|B\rangle$ in the decay amplitude. These form factors are defined in the Appendix.

The phenomenological model presented in here has the peculiarity that it gives no contribution of the J/ψ resonance to the radiative B decays, when the $b \to sJ/\psi$ transition is treated within the factorization approximation. In that approximation, as was shown above, $g_2 = 0$, and so there is no J/ψ contribution to the magnetic dipole moment structure in the $bs\gamma$ vertex. This result can be understood from a different perspective. The Hamiltonian in Eq. (5) gives a perturbative contribution to $G_{1,2}^{c\bar{c}}$ that, at the lowest order, corresponds to the c-quark loop diagram in Fig. 2. This gives $G_2^{c\bar{c}} = 0$ and $G_1^{c\bar{c}} = (C_2 + C_1/3)eQ_c\Pi(k^2)$, where $\Pi(k^2)$ has a cut along the real axis starting at $k^2 = 4m_c^2$, and no poles. This contribution is to be interpreted as an average over the c-$\bar{c}$ resonant and continuum virtual states. In order to obtain the poles, such as the J/ψ pole, explicitly, soft QCD effects would have to be included. In particular, the soft gluon exchanges between the c-quark lines inside the loop would yield the c-$\bar{c}$ bound states. This would result in including the J/ψ pole in $\Pi(k^2)$, but there would still be no contribution to $G_2^{c\bar{c}}$. The latter, and the associated magnetic dipole moment structure of the $bs\gamma$ vertex, can only appear due to gluon exchanges between the quark lines inside the loop and the external quark lines, i.e., beyond the factorization approximation [16].

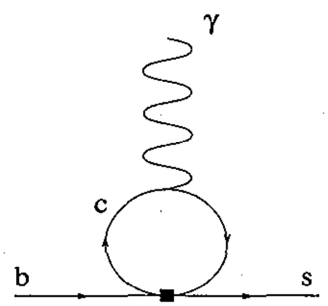

FIG. 2. The lowest order perturbative contribution, from the effective Hamiltonian in Eq. (5), to the form factors $G_{1,2}^{c\bar{c}}$ in the $bs\gamma$ vertex.

III. QUANTITATIVE ESTIMATES

In order to obtain a quantitative estimate for the size of the J/ψ contribution to the radiative B decays, in Eqs. (13) and (14), it is necessary to determine the size of g_2 in the bsJ/ψ vertex. One possibility would be to extract $g_{1,2}(m_{J/\psi}^2)$ from the experimental values for the branching ratio, $B(B \to J/\psi + \text{anything}) = (1.15 \pm 0.07)\%$ [17], and the polarization, $\Gamma_L/\Gamma = 0.59 \pm 0.15$ [17], in the inclusive decay. This can only be done after removing from the data the contribution from the B decays into ψ' and χ_{c1}, which in turn decay into J/ψ. The effect on the branching ratio has been measured, and $B(b \to sJ/\psi) = (0.82 \pm 0.08)\%$ [17] for the direct decay, but the effect on the polarization has not, and so Γ_L/Γ

for the direct decay could range from 0.18 to 1. This large uncertainty is not the major obstacle in extracting $g_{1,2}$ from the inclusive $b \to sJ/\psi$ data; because the longitudinal and transversal decay rates are not sensitive to the sign of the corresponding amplitudes, $g_{1,2}$ can only be determined up to a fourfold ambiguity. The ambiguity is particularly serious for an estimate of $g_2(m^2_{J/\psi})$. For example, if the J/ψ mesons from the cascade decays are unpolarized, then $\Gamma_L/\Gamma = 0.69 \pm 0.21$ for the direct decay; taking $|V_{cb}| = 0.038\sqrt{1.63 \text{ psec}/\tau_b}$ [18] and $m_b = 5.0$ GeV in

$$\Gamma_{L,T}(b \to sJ/\psi) = \frac{1}{8\pi} G_F^2 |V_{cb}V_{cs}^*|^2 (C_2 + \tfrac{1}{3}C_1)^2 m_b \left(1 - \frac{m^2_{J/\psi}}{m_b^2}\right)^2 \times \begin{cases} [g_1(m^2_{J/\psi}) - g_2(m^2_{J/\psi})]^2 m_b^2 m^2_{J/\psi} & \text{(L)}, \\ 2\,[g_1(m^2_{J/\psi}) m^2_{J/\psi} - g_2(m^2_{J/\psi}) m_b^2]^2 & \text{(T)}, \end{cases} \tag{15}$$

gives (up to a sign) $g_2(m^2_{J/\psi}) = 0.26 \pm 0.03$ or 0.04 ± 0.07, which are very different in magnitude.

The alternative is to extract $g_{1,2}(m^2_{J/\psi})$ from the data for the exclusive decays. The branching ratio and the polarization for the $B \to K^* J/\psi$ decay [17],

$$B(B \to K^* J/\psi) = (1.64 \pm 0.27) \times 10^{-3}, \tag{16}$$

$$\left(\frac{\Gamma_L}{\Gamma}\right)_{B \to K^* J/\psi} = 0.78 \pm 0.07, \tag{17}$$

allow one to determine $g_{1,2}$, up to the same fourfold ambiguity as in the inclusive case. But here the additional $B \to K J/\psi$ branching ratio [17]

$$B(B \to K J/\psi) = (0.089 \pm 0.013)\% \tag{18}$$

can be used to reduce the ambiguity to that in the overall sign of $g_{1,2}$. The longitudinal and transversal $B \to K^* J/\psi$ decay amplitudes are

$$\begin{aligned} A_L(B \to K^* J/\psi) = &-\frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* (C_2 + \tfrac{1}{3}C_1) \frac{m_{J/\psi}}{2m_{K^*}} \Bigg\{ g_1(m^2_{J/\psi})(m_B + m_{K^*}) \Bigg[A_1(m^2_{J/\psi})(m_B^2 - m_{K^*}^2 - m^2_{J/\psi}) \\ &- A_2(m^2_{J/\psi}) \frac{4m_B^2 |\vec{k}|^2}{(m_B + m_{K^*})^2} \Bigg] + g_2(m^2_{J/\psi}) m_b \Bigg[-F_2(m^2_{J/\psi})(m_B^2 + 3m_{K^*}^2 - m^2_{J/\psi}) \\ &+ F_3(m^2_{J/\psi}) \frac{4m_B^2 |\vec{k}|^2}{m_B^2 - m_{K^*}^2} \Bigg] \Bigg\} \end{aligned} \tag{19}$$

and

$$\begin{aligned} A_T(B \to K^* J/\psi) = &-\frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* (C_2 + \tfrac{1}{3}C_1)(m_B + m_{K^*}) \\ &\times \sum_{\pm} \Bigg\{ g_1(m^2_{J/\psi}) m^2_{J/\psi} \Bigg[-A_1(m^2_{J/\psi}) \mp V(m^2_{J/\psi}) \frac{2m_B |\vec{k}|}{(m_B + m_{K^*})^2} \Bigg] \\ &+ g_2(m^2_{J/\psi}) m_b (m_B - m_{K^*}) \Bigg[F_2(m^2_{J/\psi}) \mp F_1(m^2_{J/\psi}) \frac{m_B |\vec{k}|}{m_B^2 - m_{K^*}^2} \Bigg] \Bigg\}, \end{aligned} \tag{20}$$

respectively; the $B \to K J/\psi$ decay amplitude is

$$A(B \to K J/\psi) = -\frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* (C_2 + \tfrac{1}{3}C_1) 2m_B |\vec{k}| m_{J/\psi} \left[g_1(m^2_{J/\psi}) f_1(m^2_{J/\psi}) + g_2(m^2_{J/\psi}) m_b s(m^2_{J/\psi}) \right] \tag{21}$$

($|\vec{k}|$ is the J/ψ momentum in the B rest frame). The hadronic matrix elements $\langle K^{(*)}|\bar{s}\gamma_\nu L b|B\rangle$ and $\langle K^{(*)}|\bar{s}i\sigma^{\mu\nu}k_\nu R b|B\rangle$ have been parametrized in terms of the form factors V, $A_{0,1,2}$, $f_{0,1}$, and $F_{1,2,3}$, s, respectively, as defined in the Appendix. In order to minimize the uncertainty that is inherent to any particular model for these form factors, one can choose instead to relate them to the form factors that can be measured in semileptonic decays. In Ref. [19], Isgur and Wise have used the heavy quark symmetry (HQS) to related the $B \to K^{(*)}$ form factors to the form factors in $D \to K^{(*)} l \bar{\nu}_l$; their method will be used in here, and the results are summarized in the Appendix. It must be pointed out that these results are not entirely model independent, as some assumption must be made regarding the k^2 dependence of the form factors [20]. The associated uncertainty is hard to quantify and will not appear in the results, but it should be kept in mind.

When compared to the experimental results, the magnitude of the amplitudes in Eqs. (19)–(21) gives the straight lines

$$g_1 = \pm a_i + b_i g_2 \qquad (i = 1,2,3) \tag{22}$$

in the (g_1, g_2) plane (for the transverse amplitude the exact solution does not give a straight line, but this is a very good approximation in the region of interest). The parameters a_i and b_i are listed in Table I; the errors reflect the uncertainties in Eqs. (16)–(18) and in the normalization of the $B \to K^{(*)}$ form factors [see Eq. A16, in the Appendix]. The corresponding allowed regions are shown in Fig. 3, and their overlap gives

$$|g_1(m^2_{J/\psi})| = 0.31\text{–}0.38, \quad |g_2(m^2_{J/\psi})| = 0.05\text{–}0.10 \tag{23}$$

(an ambiguity in the overall sign of $g_{1,2}$ remains). These results are also sensitive to the values of the Wilson coefficients $C_{1,2}$ and of $|V_{cb}|\sqrt{\tau_b}$ that were chosen. The associated errors, although large, were not included as they will not affect the results that follow.

Finally, the J/ψ contribution to the radiative B decay amplitudes, in Eqs. (13) and (14), can be compared to the experimental values for the full amplitudes, from Eqs. (1) and (2). For the inclusive decay,

$$\frac{|A(b \overset{J/\psi}{\to} s\gamma)|}{|A(b \to s\gamma)|_{\rm expt}} = 0.15 \pm 0.05, \tag{24}$$

and, for the exclusive decay,

$$\frac{|A(B \overset{J/\psi}{\to} K^*\gamma)|}{|A(B \to K^*\gamma)|_{\rm expt}} = \frac{F_1(0)}{0.96} \times (0.12 \pm 0.05). \tag{25}$$

As pointed out above, these results are not affected by the uncertainties in $|V_{cb}|\sqrt{\tau_b}$ and in $|C_2 + C_1/3|$. The errors indicated correspond to the uncertainties in Eq. (23), and in the experimental branching ratios for the radiative decays. For the exclusive case, an additional uncertainty is associated with the value of $F_1(0)$. In here, $F_1(0) = 0.96 \pm 0.11$ (see the Appendix), but it is smaller in other popular models for the $B \to K^*$ form factors (in the Bauer-Stech-Wirbel (BSW) model [21] $F_1(0) = 0.69$ and in the Jaus-Wyler (JW) model [22] $F_1(0) = 0.59$). Finally, it should be pointed out that the sign of g_2 could not be determined; thus, it cannot be said whether the long and short distance contributions to the radiative B decay amplitudes interfere destructively or constructively.

TABLE I. The parameters for the lines $g_1 = \pm a_i + b_i g_2$ $(i = 1,2,3)$ in Fig. 3.

i	a_i	b_i
1	0.32 ± 0.07	1.41 ± 0.14
2	0.15 ± 0.03	2.63
3	0.29 ± 0.03	0.57

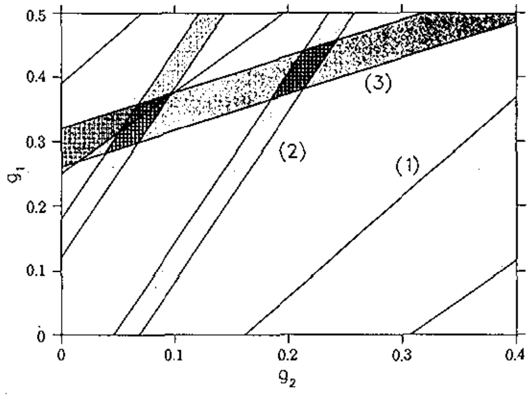

FIG. 3. Allowed region on the (g_1, g_2) plane, from the data for the longitudinal (1) and transversal (2) $B \to K^* J/\psi$ rates, and for the $B \to K J/\psi$ rate (3).

IV. CONCLUSION

A phenomenological model was constructed that describes the contribution to the radiative B decays from the tree-level decay into the J/ψ resonance, followed by the J/ψ-photon conversion. To account for the weak decay, an effective bsJ/ψ vertex was introduced, which is used to describe both the inclusive and the exclusive B decays into J/ψ. This assumes that the hadronization effects in the J/ψ production and in the $B \to K^{(*)}$ transition can be treated separately. The latter can then be described in terms of the usual set of form factors, related to those in semileptonic decays, whereas the former are described in terms of a new set of form factors that are determined empirically. The J/ψ-photon transition is modeled after the VMD ideas that were used, for example, to describe the ρ-meson contribution to the nucleon electromagnetic form factors. The assumption in here is that of complete J/ψ dominance of the electromagnetic form factors; i.e., the other c-$\bar{c}$ contributions are neglected. This leads to a Lagrangian for the J/ψ-photon interaction, parametrized by the J/ψ decay constant.

Within this model, the J/ψ contribution to the B-meson radiative decays was estimated to be (10–20)% of the observed $b \to s\gamma$ amplitude and (7–17)% of the $B \to K^*\gamma$ amplitude. The large uncertainties correspond mostly to experimental errors and will be reduced in the future. There is, however, an additional uncertainty from some degree of model dependence in extracting the form factors in the bsJ/ψ vertex from the data. Also not shown explicitly are the errors inherent to the assumptions that underlie the phenomenological model. In particular, the assumption of complete VMD is probably too strong. It has been suggested [23] that the effect of c-$\bar{c}$ contributions other than the J/ψ meson can be included in the formalism derived from the complete VMD assumption, by allowing for an effective k^2 dependence of $f_{J/\psi}$. Within this prescription, the data for J/ψ photoproduction and for charmonium radiative decays reveal a significant departure from complete VMD [24, 10]. In Ref. [24], it is found that

$$\frac{f_{J/\psi}(0)}{f_{J/\psi}(m^2_{J/\psi})} \sim 0.6, \quad (26)$$

which should be viewed as a suppression factor that multiplies the results given here. However, the size of this suppression is uncertain, and the k^2 dependence of the form factors in the bsJ/ψ vertex remains unknown. For these reasons, the results consistent with the complete VMD assumption were reported in here, while corrections to this assumption await further work.

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APPENDIX

The hadronic matrix elements in the decay amplitudes are parametrized as follows:

$$\langle K^*(p',\varepsilon')|\bar{s}\gamma^\mu Lb|B(p)\rangle = \frac{-1}{m_B+m_{K^*}} 2i\epsilon^{\mu\alpha\beta\gamma}\varepsilon'^*_\alpha p'_\beta p_\gamma V(k^2) - (m_B+m_{K^*})\varepsilon'^{\mu *}A_1(k^2) + \frac{\varepsilon'^*\cdot k}{m_B+m_{K^*}}(p+p')^\mu A_2(k^2) + 2m_{K^*}\frac{\varepsilon'^*\cdot k}{k^2}k^\mu[A_3(k^2)-A_0(k^2)], \quad \text{(A1)}$$

where

$$2m_{K^*}A_3(k^2) \equiv (m_B+m_{K^*})A_1(k^2) - (m_B-m_{K^*})A_2(k^2) \quad \text{(A2)}$$

and $A_0(0)=A_3(0)$,

$$\langle K^*(p',\varepsilon')|\bar{s}i\sigma^{\mu\nu}k_\nu Rb|B(p)\rangle = i\epsilon^{\mu\alpha\beta\gamma}\varepsilon'^*_\alpha p'_\beta p_\gamma F_1(k^2) + [(m_B^2-m_{K^*}^2)\varepsilon'^{\mu *} - \varepsilon'^*\cdot k(p+p')^\mu]F_2(k^2) + \varepsilon'^*\cdot k\left[k^\mu - \frac{k^2}{m_B^2-m_{K^*}^2}(p+p')^\mu\right]F_3(k^2), \quad \text{(A3)}$$

where $F_1(0)=2F_2(0)$,

$$\langle K(p')|\bar{s}\gamma^\mu Lb|B(p)\rangle = (p+p')^\mu f_1(k^2) + \frac{m_B^2-m_K^2}{k^2}k^\mu[f_0(k^2)-f_1(k^2)], \quad \text{(A4)}$$

where $f_1(0)=f_0(0)$, and

$$\langle K(p')|\bar{s}i\sigma^{\mu\nu}k_\nu Rb|B(p)\rangle = s(k^2)[(p+p')^\mu k^2 - (m_B^2-m_K^2)k^\mu] \quad \text{(A5)}$$

($k=p-p'$; $L,R\equiv 1\mp\gamma_5$).

In Ref. [19], Isgur and Wise pointed out that in the static b-quark limit $\gamma_0 b = b$, in the B-meson rest frame, and so the $\langle K^{(*)}|\bar{s}\gamma^\mu Lb|B\rangle$ and $\langle K^{(*)}|\bar{s}i\sigma^{\mu\nu}k_\nu Rb|B\rangle$ form factors are related by

$$F_1(k^2) = 2(m_B-E_{K^*})\frac{V(k^2)}{m_B+m_{K^*}} + \frac{m_B+m_{K^*}}{m_B}A_1(k^2), \quad \text{(A6)}$$

$$F_2(k^2) = \frac{2m_B|\vec{p}_{K^*}|^2}{m_B^2-m_{K^*}^2}\frac{V(k^2)}{m_B+m_{K^*}} + \frac{m_B-E_{K^*}}{m_B-m_{K^*}}A_1(k^2), \quad \text{(A7)}$$

$$F_3(k^2) = (m_B+E_{K^*})\frac{V(k^2)}{m_B+m_{K^*}} - \frac{m_B^2-m_{K^*}^2}{m_B}\left\{\frac{V(k^2)}{m_B+m_{K^*}} + \frac{1}{2}\frac{1}{m_B-m_{K^*}}A_1(k^2) - \frac{1}{2}\frac{1}{m_B+m_{K^*}}A_2(k^2) + \frac{m_{K^*}}{k^2}[A_3(k^2)-A_0(k^2)]\right\} \quad \text{(A8)}$$

(where E_{K^*} and $|\vec{p}_{K^*}|$ are the energy and momentum of the K^* meson in the B rest frame), and

$$s(k^2) = \frac{1}{2m_B}\left\{-f_1(k^2) + \frac{m_B^2-m_K^2}{k^2}[f_0(k^2)-f_1(k^2)]\right\}. \quad \text{(A9)}$$

The $B\to K^{(*)}$ form factors V, $A_{0,1,2}$, and $f_{+,-}$ are then related to the analogous $D\to K^{(*)}$ form factors, through the HQS relations [19]

$$V(t^*) = \left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{-6/25}\sqrt{\frac{m_c}{m_b}}\,\frac{m_B+m_{K^*}}{m_D+m_{K^*}}\,V^{DK^*}(0), \quad \text{(A10)}$$

TABLE II. The pole masses [21] for the $B, D \to K^{(*)}$ form factors.

	V	$A_{1,2}$	A_0	f_1	f_0
$D \to K^{(*)}$	2.11	2.53	1.97	2.11	2.60
$B \to K^{(*)}$	5.43	5.82	5.38	5.43	5.89

$$A_1(t^*) = \left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{-6/25} \sqrt{\frac{m_b}{m_c}}\, \frac{m_D + m_{K^*}}{m_B + m_{K^*}}\, A_1^{DK^*}(0), \tag{A11}$$

$$A_2(t^*) = \frac{1}{2}\left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{-6/25} \sqrt{\frac{m_c}{m_b}}\, \frac{m_B + m_{K^*}}{m_D + m_{K^*}} \left\{ \left(1 + \frac{m_c}{m_b}\right) A_2^{DK^*}(0) + \left(1 - \frac{m_c}{m_b}\right)(m_D + m_{K^*}) 2m_{K^*} \left[\frac{A_0^{DK^*}(k^2) - A_3^{DK^*}(k^2)}{k^2}\right]_{k^2=0} \right\}, \tag{A12}$$

and

$$f_1(t) = \frac{1}{2}\left(\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right)^{-6/25} \sqrt{\frac{m_b}{m_c}} \left\{ \left(1 + \frac{m_c}{m_b}\right) f_1^{DK}(0) - \left(1 - \frac{m_c}{m_b}\right)(m_D^2 - m_K^2) \left[\frac{f_0^{DK}(k^2) - f_1^{DK}(k^2)}{k^2}\right]_{k^2=0} \right\}, \tag{A13}$$

with

$$t^{(*)} = m_b^2 + m_{K^{(*)}}^2 - \frac{m_b}{m_c}\,(m_c^2 + m_{K^{(*)}}^2). \tag{A14}$$

The $D \to K^{(*)}$ form factors, at $k^2 = 0$, are extracted from the $D \to K^{(*)} l \bar{\nu}_l$ data, assuming a monopole k^2 dependence as in the BSW model [21] (see Table II for the pole masses). They are [25]

$$V^{DK^*}(0) = 1.12 \pm 0.16, \qquad A_1^{DK^*}(0) = 0.61 \pm 0.05,$$
$$A_2^{DK^*}(0) = 0.45 \pm 0.09, \qquad f_1^{DK}(0) = 0.77 \pm 0.04. \tag{A15}$$

For the other parameters, the values used in here are $m_b = 5.0$ GeV, $m_c = (1.5 \pm 0.2)$ GeV, and $\Lambda^{(4)}_{\overline{\rm MS}} = (250 \pm 50)$ MeV [13].

The k^2 dependence of the $B \to K^{(*)}$ form factors is not determined by the HQS relations. As for the $D \to K^{(*)}$ form factors, it will be assumed that it is the monopole dependence of the BSW model (see also Refs. [26] and [27]). The pole masses are given in Table II, and

$$V(0) = 0.73 \pm 0.13, \qquad A_1(0) = 0.30 \pm 0.03,$$
$$A_2(0) = 0.31 \pm 0.05, \qquad f_1(0) = 0.50 \pm 0.03, \tag{A16}$$

from Eqs.(A10)–(A13).

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