Difficulties in Explaining Recent Data on $B \to J/\psi + K(K^*)$ Decays with Commonly Used Form Factors within the Factorization Approach

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Assuming factorization, we establish restrictions on $B \to K$ (K^*) form factors imposed by recent data on $B \to J/\psi + K$ (K^*) decay rates and polarization. We show that these constraints are not satisfied by commonly used models. In addition, we relate $B \to K$ (K^*) form factors to those in $D \to K$ (K^*) transitions using the heavy flavor symmetry as proposed by Isgur and Wise and discuss the uncertainties in this procedure. We find that this method also leads to form factors excluded by data.

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It is generally believed that the best place to study the importance of color-suppressed processes in B meson decay is to look at final states involving a charmonium and a strange meson [1]. Aside from the color-suppressed process, penguin diagrams can also contribute to such decays. However, as at least two gluons are needed to excite the $\chi_{C1}(1P)$ state, and at least three for J/ψ and $\psi(2S)$, we neglect the contribution of the penguin processes.

Here, we restrict our discussion to the only observed processes [2] of this kind, for both neutral and charged B and K (K^*),

$$B \to J/\psi + K\ (K^*). \tag{1}$$

The computation of the branching ratios for the decays in (1) in the factorization approximation is straightforward. The resulting branching ratio for the process in (1) can be conveniently written as [1]

$$B(B \to J/\Psi + K) = N|V_{cb}|^2 a_2^2 |F_1^{BK}(m_{J/\Psi}^2)|^2 \times (\tau_B/10^{-12}\ \mathrm{s}), \tag{2}$$

$$B(B \to J/\psi + K^*)_{\lambda\lambda} = N^*|V_{cb}|^2 a_2^2 |A_1^{BK^*}(m_{J/\psi}^2)|^2 \times \Sigma_{\lambda\lambda}(\tau_B/10^{-12}\ \mathrm{s}), \tag{3}$$

where the polarization-dependent quantity $\Sigma_{\lambda\lambda}$ has the structure

$$\Sigma_{LL} = (a - bx)^2, \quad \Sigma_{TT} = 2(1 + c^2y^2), \tag{4}$$

L and T standing for longitudinal and transverse for both final vector mesons. The other quantities in Eqs. (2)–(4) are defined as follows: All color-suppressed amplitudes are proportional to the parameter a_2 [3]. We have also used the notation of [3] for the form factors. The normalization constants N and N^* depend on the masses, on the Cabihbo-Kobayashi-Maskawa factor $|V_{cs}| = 0.974$, and on the leptonic decay constant $f_{J/\psi}$, estimated from $J/\psi \to e^+e^-$ decay to be $f_{J/\psi} = 382$ MeV. The sensitivity of N and N^* on the neutral or charged strange meson mass appears at the level of 1 part in 10^3; hence we ignore the mass differences between K^0 and K^+, K^{*0} and K^{*+}. We obtain

$$N = 10.845\left(\frac{f_{J/\psi}}{382\ \mathrm{MeV}}\right)^2, \quad N^* = 11.723\left(\frac{f_{J/\psi}}{382\ \mathrm{MeV}}\right)^2. \tag{5}$$

In (4) the dimensionless coefficients a, b, and c are given by

$$a = \frac{m_B^2 - m_{K^*}^2 - m_{J/\psi}^2}{2m_{K^*}m_{J/\psi}} = 3.1475,$$
$$b = \frac{2K^2m_B^2}{m_{K^*}m_{J/\psi}(m_B + m_{K^*})^2} = 1.2969, \tag{6}$$
$$c = \frac{2Km_B}{(m_B + m_{K^*})^2} = 0.4345,$$

where K is the c.m. momentum. In (6) we have evaluated a, b, and c for the neutral mode; the sensitivity of the fractional polarization on charged particle masses is negligible.

In Eq. (4), the parameters x and y are the ratios of hadronic form factors at the J/ψ mass

$$x = \frac{A_2^{BK^*}(m_{J/\psi}^2)}{A_1^{BK^*}(m_{J/\psi}^2)}, \quad y = \frac{V^{BK^*}(m_{J/\psi}^2)}{A_1^{BK^*}(m_{J/\psi}^2)}. \tag{7}$$

Let us now consider the following two experimental data from CLEO II [2]: (i) The ratio of vector to pseudoscalar production rates,

$$R = \frac{\Gamma(B \to J/\psi + K^*)}{\Gamma(B \to J/\psi + K)} = 1.64 \pm 0.34. \tag{8}$$

(ii) The fraction of longitudinal polarization in $B \to J/\psi + K^*$ decay,

$$\frac{\Gamma_L}{\Gamma} = \frac{\Gamma(B \to J/\psi + K^*)_{LL}}{\Gamma(B \to J/\psi + K^*)} = 0.84 \pm 0.06 \pm 0.08. \tag{9}$$

It is important to note here that the ARGUS group found $\Gamma_L/\Gamma > 0.78$ at 90% C.L. [2,4]. Assuming factorization, the theoretical expressions for R and Γ_L/Γ are

$$R_{\mathrm{th}} = 1.0809\frac{|A_1^{BK^*}(m_{J/\psi}^2)|^2}{|F_1^{BK^*}(m_{J/\psi}^2)|^2}\{(a - bx)^2 + 2(1 + c^2y^2)\} \tag{10}$$

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and

$$\left[\frac{\Gamma_L}{\Gamma}\right]_{\rm th} = \frac{(a - bx)^2}{(a - bx)^2 + 2(1 + c^2y^2)}. \tag{11}$$

We begin by comparing theory with experiment, purely phenomenologically, with a view to set limits on the parameters that enter expressions (10) and (11). It is convenient to discuss the ratio Γ_L/Γ first. In Fig. 1 we have plotted the fraction Γ_L/Γ in the x, y plane. The curves of Eq. (11) at fixed Γ_L/Γ are hyperbolas centered at the point $x = a/b = 2.43$ and $y = 0$; the second branch of the hyperbolas not represented in Fig. 1 has been disregarded as unphysical, because it would require too large values of x ($x \simeq 2a/b$) to fit experiments. In Fig. 1 we have also shown the one standard deviation lower bound $\Gamma_L/\Gamma > 0.74$ from CLEO II data. We also observe that there exists a theoretical upper bound $(\Gamma_L/\Gamma)_{\rm th} \leq a^2/(2 + a^2)$, which on using (6) yields $(\Gamma_L/\Gamma)_{\rm th} \leq 0.832$, which is clearly consistent with experiment. The bounds on x and y set by $\Gamma_L/\Gamma > 0.74$, shown by the shaded area in Fig. 1, are

$$x \leq 0.59, \quad y \leq 1.98. \tag{12}$$

We assume the ratios x and y to be positive as is implied by all theoretical models that we are aware of. Of course, with only one experimental quantity Γ_L/Γ, it is not possible to determine x and y separately—the separation of the two transverse polarizations is necessary

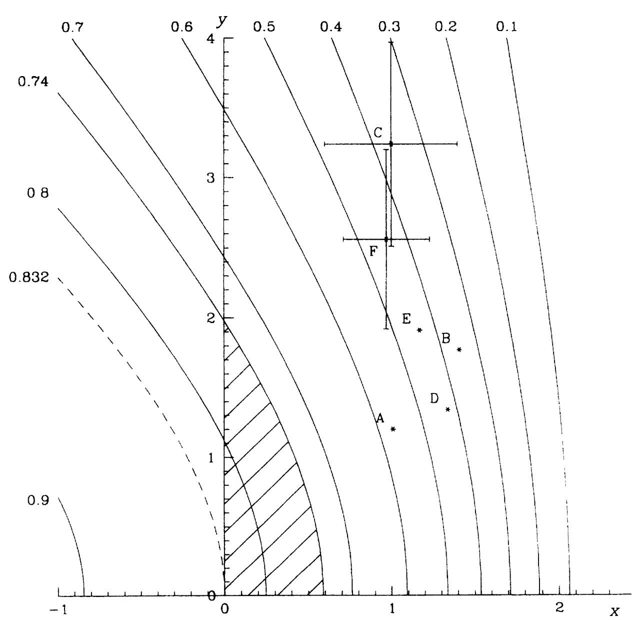

FIG. 1. The polarization fraction Γ_L/Γ in the x, y plane. The solid curves correspond to fixed values of Γ_L/Γ as indicated. The dashed curve is the theoretical upper bound $\Gamma_L/\Gamma = 0.832$. The shaded region is the allowed region corresponding to $\Gamma_L/\Gamma > 0.74$. The six points correspond to the predictions of the models defined in the text: A, BSW I; B, BSW II; C, CDDFGN; D, HSQ; E, JW; F, Isgur-Wise procedure. Errors are shown when available.

for obtaining y—nevertheless the allowed domain in the x, y plane is small enough to constrain the quantity $\Sigma_{LL} + \Sigma_{TT}$ associated with the unpolarized rate. From the allowed domain in the x, y plane corresponding to $\Gamma_L/\Gamma > 0.74$, we get

$$7.7 \leq (a - bx)^2 + 2(1 + c^2y^2) \leq 13.4. \tag{13}$$

Next we consider $R_{\rm th}$ of Eq. (10), which we write in the form

$$R_{\rm th} = 1.0809\,\frac{(a - bx)^2 + 2(1 + c^2y^2)}{z^2}, \tag{14}$$

where we have introduced a parameter z defined by

$$z = \frac{F_1^{BK}(m_{J/\psi}^2)}{A_1^{BK^*}(m_{J/\psi}^2)}. \tag{15}$$

Using the CLEO II result for R, Eq. (8), and the bounds in (13), we obtain the following allowed range for z,

$$2.05 \leq z \leq 3.34. \tag{16}$$

Having experimental data on R and Γ_L/Γ and the associated limits on x, y, and z derived by us in (12) and (16), we now investigate the predictions of various theoretical models. We consider five such models:

(i) The original Bauer-Stech-Wirbel (BSW) model [3] (called BSW I here) where the value of the form factors is calculated at $q^2 = 0$ and extrapolated to finite q^2 using a monopole form for all the form factors F_1, A_1, A_2, and V.

(ii) A modified BSW model (called BSW II here) takes the values of the form factors at $q^2 = 0$ as in BSW I but uses a monopole extrapolation for A_1 and a dipole extrapolation for F_1, A_2, and V [5].

(iii) The model of Casalbuoni *et al.* [6] and Deandrea *et al.* [7], where the normalization at $q^2 = 0$ is obtained in a model that combines heavy quark symmetry with chiral symmetry for light pseudoscalar degrees of freedom and also introduces light vector degrees of freedom. We call this the CDDFGN model. Here all form factors are extrapolated with monopole forms as in Ref. [7].

(iv) We consider a heavy quark type model in which both b and s quarks are treated as heavy (we label this model HSQ for "heavy strange quark"). Such a model has been used by Ali *et al.* [8] in studying $D \to (K, K^*)l\nu$, $B \to K^*\gamma$, and $B \to (K, K^*)l\bar{l}$. In our calculations, the four form factors are expressed in terms of a universal Isgur-Wise function where the extrapolation from the symmetry point $q^2 = q_{\rm max}^2$ to $q^2 = m_{J/\psi}^2$ is made by using an improved form of the relativistic oscillator model as described in [9].

(v) A relativistic constituent quark model due to Jaus and Wyler (JW) [10] which uses light-front formalism to compute the form factors in the spacelike momentum transfer region. The form factors are then extrapolated to the timelike region by a particular two-parameter formula, described in [10], which, for $q^2 = 0$, reproduces the value of the form factors and their first two derivatives.

In Table I we have tabulated the values of R, Γ_L/Γ, x, y, and z obtained in these five models. The first two have to be compared with experiments, Eqs. (8) and (9), the last three with our constraints (12) and (16).

Both BSW I and HSQ models are clearly ruled out by the ratio of the rates R, the latter faring worse than the former. (This is not surprising as such a model is also known [8] to overestimate the semileptonic rates $D \to (K, K^*)l\nu$ by a factor of 2. Our analysis clearly demonstrates that treating the s quark as heavy is a poor approximation.) The JW model overestimates R moderately. The remaining two models BSW II and CDDFGN are consistent with data on R within experimental errors.

However, the situation takes a dramatic turn for Γ_L/Γ, where *none* of the five models considered reproduce the large longitudinal polarization fraction observed experimentally—equivalently the allowed domain in the x, y plane excludes the values of x and y produced by all of these models. See Fig. 1 where the x, y parameters produced by these models are shown.

The five models we have discussed here being unable to account for both CLEO II data on R and Γ_L/Γ, it is interesting to seek some other way to obtain $B \to K$ and $B \to K^*$ hadronic form factors with as little model dependence as possible. This can be achieved by relating $B \to (K, K^*)$ form factors to the measured $D \to (K, K^*)$ form factors in, at least, two different ways: one, using the method of heavy quark symmetry combined with chiral symmetry incorporating the light vector degrees of freedom [6,7,11] and, second, by using the method of Isgur and Wise [12]. We choose the latter as it is based on general principles of scaling and heavy flavor symmetry.

Following a procedure described in detail in [1] and using the experimental input on $D \to (K, K^*)$ form factors from [13], we obtain, with $m_b = 5.0$ GeV, $m_c = 1.5$ GeV [1],

$$\begin{aligned} F_1^{BK}(m_{J/\psi}^2) &= 0.75 \pm 0.05, \\ A_1^{BK^*}(m_{J/\psi}^2) &= 0.43 \pm 0.04, \\ A_2^{BK^*}(m_{J/\psi}^2) &= 0.42 \pm 0.07, \\ V^{BK^*}(m_{J/\psi}^2) &= 1.10 \pm 0.17. \end{aligned} \tag{17}$$

The form factors of (17) lead to

$$x = 0.97 \pm 0.26, \quad y = 2.56 \pm 0.64. \tag{18}$$

The corresponding point is shown in Fig. 1 and is clearly outside the allowed domain defined by $\Gamma_L/\Gamma > 0.74$. From the range x and y in (18), the value of the longitudinal polarization fraction is found to be

$$\frac{\Gamma_L}{\Gamma} = 0.45^{+0.13}_{-0.17}, \tag{19}$$

which differs from the experimental value (9) by more than two standard deviations. Thus the Isgur-Wise procedure to derive the $B \to (K, K^*)$ form factors from the $D \to (K, K^*)$ ones also fails in producing form factors consistent with (Γ_L/Γ) and R data.

The problem may be due to the procedure, and we shall discuss this point later, or it may well be with the input $D \to (K, K^*)$ form factors, in particular $A_2^{DK^*}$ and V^{DK^*}. The earlier E-691 determination [14] of $A_2^{DK^*}(0)$ was consistent with zero. Later measurements by E-653 [15] and E-687 [16] Collaborations led to a larger $A_2^{DK^*}(0)$. It is these larger values of $A_2^{DK^*}(0)$ which are being reflected as larger values of $A_2^{BK^*}(m_{J/\psi}^2)$ through the Isgur-Wise procedure. The value of $V^{BK^*}(m_{J/\psi}^2)$ is also too high; however, the error in the input value $V^{DK^*}(0)$ is also large and with a generous treatment of errors, $V^{BK^*}(m_{J/\psi}^2)$ could well be within the y bound (12) set by us. The major problem is with $A_2^{BK^*}(m_{J/\psi}^2)$ or equivalently the parameter x.

Returning now to a discussion of theoretical procedure in deriving $B \to (K, K^*)$ form factors from $D \to (K, K^*)$ ones, we wish to emphasize two sources of uncertainties: the choice of b and c quark masses, and the type of q^2 extrapolation employed. Addressing ourselves to the former, we repeated our calculation replacing m_b by m_B and m_c by m_D. Within errors, however, the two results were consistent confirming that there is little dependence on m_b and m_c, if chosen reasonably.

The type of q^2 dependence of the hadronic form factors poses a more serious problem. We have used a monopole form for all $D \to (K, K^*)$ and $B \to (K, K^*)$ form factors for the simple reason that $D \to (K, K^*)$ experiments have been analyzed [13] with such forms. This ansatz could be incorrect at least for some form factors; we already know that for heavy to heavy quark transition, consistency with the heavy quark limit requires the q^2 dependence of $F_1(q^2)$, $V(q^2)$, and $A_2(q^2)$ to differ from that of $A_1(q^2)$ by

TABLE I. Tabulation of R, Γ_L/Γ, x, y, and z.

	BSW I	BSW II	CDDFGN	HSQ	JW	
R	4.25	1.61	1.50	8.97	2.44	1.64 ± 0.34[a]
Γ_L/Γ	0.57	0.35	0.36	0.43	0.44	0.84 ± 0.10[b]
x	1.01	1.41	1.00	1.34	1.17	≤ 0.59[c]
y	1.20	1.77	3.24	1.34	1.91	≤ 1.98[c]
z	1.23	1.82	2.60	0.75	1.64	$2.05 \leq z \leq 3.34$[d]

[a]Equation (8).
[b]Equation (9).
[c]Equation (12).
[d]Equation (16).

an additional pole factor [5]. However, for heavy to light quark transitions, to the best of our knowledge, there is no convincing argument as to the type of q^2 dependence to be employed. At the other extreme, QCD sum rules seem to indicate that for the hadronic form factor $A_1(q^2)$, a single monopole form may be questionable, and instead of growing with positive q^2, $A_1(q^2)$ may be almost constant or even decreasing [17]. However, such a feature cannot drastically change the analysis.

In summary, the polarization measurements in $B \to J/\psi K^*$ by CLEO II and ARGUS groups appear as a decisive input in the analysis of this class of decays. If correct, they set very stringent limits on our ratios x and y which up to now are not theoretically understood. The six models we selected as representative ones are unable within the factorization ansatz to reproduce the data by several standard deviations. It is clear that the confirmation of the polarization measurement in $B \to J/\psi K^*$ is urgently needed. We must emphasize that the factorization assumption plays a key role not only in the analysis of the decay modes considered here, but also in the determination of the parameter a_2 from these decays, and its failure will equally pose a threat to the extraction of the C.P. violating angle, generally called β. Therefore it is important to independently test this hypothesis for color-suppressed decays involving heavy to light quark transitions. As an example, the relation between the two color-suppressed processes $B \to K\ (K^*) + \eta_c$ and $B \to K\ (K^*) + J/\psi$ could provide a test of factorization hypothesis which we are currently investigating. To date factorization in B decays has been successfully tested only in color-favored decays (amplitudes proportional to a_1), involving heavy to heavy quark transitions [5,18]. It is quite possible that the disagreement of the CLEO $B \to J/\psi + K^*$ data with our theoretical analysis is a first manifestation of the failure of the factorization in the color-suppressed beauty decays, if the data are confirmed.

If the origin of the difficulty unveiled by us is not due to a failure of factorization, a more refined study of the form factors in $B \to K\ (K^*)$ transitions is needed.

Note added.—After the paper is submitted, new experimental data $\Gamma_L/\Gamma = 0.66 \pm 0.10^{+0.08}_{-0.10}$ (CDF Collaboration, Fermilab-Conf 94/127-E CDF) are available that do not change qualitatively, however, our results (see Fig. 1 and Table I).

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