Hadronic contributions to form factors of semileptonic decays of D and B mesons

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Hadronic corrections to the form factors of semileptonic D and B decays are evaluated. It is shown that these effects cannot be responsible for the existing discrepancy between theory and experiment in the values of the ratio of longitudinal and transversal polarizations of the $\bar{K}^{0*}$ meson in the decay $D^+ \rightarrow \bar{K}^{0*} e^+ \nu$. The effects of the hadronic corrections are shown to be even weaker in the case of the $B^+ \rightarrow \bar{D}^{0*} e^+ \nu$ decay.

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I. INTRODUCTION AND GENERAL METHOD

Semileptonic decays of charmed and b -flavored hadrons are a most important source of information on fundamental parameters in the Higgs sector of the standard model of weak interactions. However, these parameters, which are elements of the Cabibbo-Kobayashi-Maskawa matrix, have to be extracted from the hadron decays taking into account the strong QCD interaction confining the quarks inside hadrons. The main source of uncertainty in the results that can thus be obtained comes from the treatment given to nonperturbative QCD.

Quark-model calculations [1–5] give in general a reasonably adequate description of nonperturbative effects despite the rather crude way of achieving chiral-symmetry breaking through nonzero constituent quark masses. However, in the case of the semileptonic decays of charmed mesons into vector mesons, $D^+ \rightarrow \bar{K}^{0*} e^+ \nu$, there is a rather poor agreement between quark-model calculations and experimental results [6–9], concerning both total rates and polarizations. A detailed study of this decay in the framework of QCD sum rules [10,11] shows better agreement with the data, except for the ratio of the longitudinal to the transversal polarizations of the $\bar{K}^{0*}$ meson. The central experimental value for this ratio is about twice as large as the theoretical result.

It was already pointed out [10,11] that, within the sum-rule approach, a large ratio for the longitudinal over the transversal polarization cannot be obtained and that, therefore, in case of the confirmation of the present experimental value, one has to look beyond the simple quark levels for sources of the disagreement. The clarification of this question is of great importance, not only for our understanding of the meson systems consisting of a charmed and a light quark, but also in view of the determination of the weak matrix elements involving bottom quarks.

It was suggested in Ref. [10] that hadronic corrections might influence the semileptonic decays and be the source for the discrepancy between theory and experiment. In

Fig. 1 we show the dominant diagram providing such a correction. In the present paper its contribution is evaluated and compared to the simple quark results of Ref. [11].

The calculation of the diagram of Fig. 1 must take into account that hadrons are not elementary particles with pointlike couplings, and therefore internal contributions of high virtuality must be suppressed. This is done in our calculation in the following way. We represent the hadronic contributions to the different form factors by a double dispersion integral

$$F(t) = \int ds \int du \frac{\rho(s, u, t)}{(s - m_D^2)(u - m_{K^*}^2)}. \quad (1)$$

The double spectral function can be obtained from Fig. 1 by using the Cutkosky rules, putting the internal lines on mass shell, so that only on-mass-shell vertex functions occur in the determination of the double spectral function. The internal contributions with high virtuality are then suppressed through cutoffs s_m and u_m in the s and u integrations.

For $t > 0$, special care has to be taken in order to determine the double spectral function $\rho(s, u, t)$ since non-Landau singularities may occur (see Ref. [11]).

II. EVALUATION OF THE HADRONIC CORRECTIONS

The vertex for the decay under consideration, namely $D^+ \rightarrow \bar{K}^{0*} e^+ \nu_e$, has the general form (in the notation of Ref. [1])

FIG. 1. Dominant hadronic contribution to the semileptonic decay $D^+ \rightarrow \bar{K}^{0*} e^+ \nu$, whose contributions to form factors are calculated in this paper.

$$\langle \bar{K}^{*0}, \lambda_{K^*} | J_\mu | D^+ \rangle = \varepsilon^{*\beta}(p_{K^*}, \lambda_{K^*}) \left[-i(m_D + m_{K^*}) A_1(t) g_{\beta\mu} + \frac{i A_2(t)}{m_D + m_{K^*}} (p_D)_\beta (p_D + p_{K^*})_\mu \right. \\ \left. + \frac{2V(t)}{m_D + m_{K^*}} \varepsilon_{\mu\beta\nu\sigma} (p_D)^\nu (p_{K^*})^\sigma + \dots \right], \quad (2)$$

where $t = (p_D - p_{K^*})^2 = (p_e + p_\nu)^2$, and where we have omitted the term proportional to $(p_D - p_{K^*})_\mu$, since it does not contribute to the decay in the limit of vanishing lepton masses. The kinematically allowed range for t is $0 \leq t \leq (m_D - m_{K^*})^2$.

In order to evaluate the double spectral function of the hadronic corrections due to the diagram of Fig. 1 we need the following ingredients.

(a) The vertex for the decay $D^* \rightarrow \bar{K}^* e \nu$, which, in a notation analogous to Eq. (2), can be decomposed as

$$\langle \bar{K}^* | J_\mu | D^*, \lambda_{D^*} \rangle = \varepsilon^\rho(p_{D^*}, \lambda_{D^*}) \left[i(m_{D^*} + m_K) B_1(t) g_{\mu\rho} - i \frac{B_2(t)}{m_{D^*} + m_K} (p_K)_\rho (p_{D^*} + p_K)_\mu \right. \\ \left. - \frac{2W(t)}{m_{D^*} + m_K} \varepsilon_{\mu\rho\nu\sigma} (p_{D^*})^\nu (p_K)^\sigma + \dots \right]. \quad (3)$$

(b) The $D^* D \pi$ vertex

$$(2\pi)^4 \delta^4(p_{D^*} + p_D + p_\pi) \frac{G_{D^*}}{\sqrt{3}} (p_D - p_\pi) \cdot \varepsilon(p_{D^*}, \lambda_{D^*}) (\chi_D \sigma \chi_{D^*}) \cdot \eta_\pi. \quad (4)$$

(c) The $\bar{K}^* \bar{K} \pi$ vertex

$$(2\pi)^4 \delta^4(p_{K^*} + p_K + p_\pi) \frac{G_{K^*}}{\sqrt{3}} (p_K - p_\pi) \cdot \varepsilon(p_{K^*}, \lambda_{K^*}) (\chi_K \sigma \chi_{K^*}) \cdot \eta_\pi. \quad (5)$$

Here χ 's are the isospinors of the isospin- $\frac{1}{2}$ mesons, η_π represents the π -meson isovector, and σ is the vector of Pauli matrices.

The coupling constants occurring in (4) and (5) are related to the corresponding total widths through

$$\Gamma_{\text{tot}} = \frac{2}{3} \frac{|\mathbf{p}^*|^3}{m_{M^*}^2} \frac{G^2}{4\pi}, \quad (6)$$

where $|\mathbf{p}^*|$ is the momentum of the decay products in the rest frame of the decaying spin-1 meson M^* with mass m_{M^*} .

The hadronic correction to the $D^+ \rightarrow \bar{K}^{*0} e \nu$ vertex due to the diagram of Fig. 1 can now be written in the form

$$\langle \bar{K}^{*0}, \lambda_{K^*} | J_\mu | D^+ \rangle^{\text{had}} = \varepsilon^{*\beta}(p_{K^*}, \lambda_{K^*}) T_{\beta\mu}^{\text{had}}, \quad (7)$$

with

$$(2\pi)^4 \delta^4(p_{D^*} - p_K - p_W) T_{\beta\mu}^{\text{had}} = \int \frac{d^4 p_{D^*} d^4 p_K d^4 p_\pi}{(2\pi)^{12}} \delta^4(p_{D^*} - p_D + p_\pi) \delta^4(p_{D^*} - p_K - p_W) \\ \times \delta(p_{K^*} - p_K - p_\pi) (2\pi)^{12} (-iG_{D^*}) (-iG_{K^*}) (p_D - p_\pi)^\alpha \\ \times i \frac{-g_{\rho\alpha} + (1/m_{D^*}^2) (p_{D^*})_\rho (p_{D^*})_\alpha}{p_{D^*}^2 - m_{D^*}^2} T_{\rho\mu}^{D^*} (p_K - p_\pi)_\beta \frac{i}{p_K^2 - m_K^2} \frac{i}{p_\pi^2 - m_\pi^2}, \quad (8)$$

where we have introduced the quantity $T_{\rho\mu}^{D^*}$ through

$$T_{\rho\mu}^{D^*} \varepsilon^\rho(p_{D^*}, \lambda_{D^*}) = \langle \bar{K} | J_\mu | D^*, \lambda_{D^*} \rangle. \quad (9)$$

From the expression (8) we obtain the double spectral functions for the form factors of $T_{\beta\mu}^{\text{had}}$ by applying the Cutkosky rules, with all internal lines put on the mass shell. Denoting by ρ_{A_1} , ρ_{A_2} , and ρ_V the double spectral functions for the hadronic correction of the form factors A_1 , A_2 , and V , respectively, we obtain

$$\rho_{A_1}(s, u, t) = \frac{G_D^* G_K^*}{16\pi^2} \frac{1}{\lambda^{1/2}(s, u, t)} \kappa(s, u, t) \frac{1}{m_D + m_K^*} \times \left[(m_{D^*} + m_K) B_1 \left[1 + \frac{s - m_\pi^2}{m_{D^*}^2} \right] + \frac{2B_2}{m_{D^*} + m_K} \left[R_1(u, t) - \frac{s - m_\pi^2}{m_{D^*}^2} R_2(t) \right] \right], \quad (10)$$

$$\rho_{A_2}(s, u, t) = \frac{G_D^* G_K^*}{16\pi^2} \frac{1}{\lambda^{1/2}(s, u, t)} (m_D + m_{K^*}) \times \left[(m_{D^*} + m_K) B_1 \left[X \left[1 + Z - \frac{s - m_\pi^2}{m_{D^*}^2} (1 - Z) \right] + \kappa(s, u, t) \frac{s - u - t}{\lambda(s, u, t)} \left[1 + \frac{s - m_\pi^2}{m_{D^*}^2} \right] \right] - \frac{2B_2}{m_{D^*} + m_K} \left[R_1(u, t) - \frac{s - m_\pi^2}{m_{D^*}^2} R_2(t) \right] \left[X(1 - Z) - \kappa(s, u, t) \frac{s - u - t}{\lambda(s, u, t)} \right] \right], \quad (11)$$

and

$$\rho_V(s, u, t) = \frac{G_D^* G_K^*}{16\pi^2} \frac{2}{\lambda^{1/2}(s, u, t)} (m_D + m_{K^*}) \kappa(s, u, t) \frac{W}{m_{D^*} + m_K}. \quad (12)$$

In the above expressions we have introduced the abbreviations

$$\lambda(s, u, t) = (s + u - t)^2 - 4su, \quad (13)$$

$$\kappa(s, u, t) = -m_\pi^2 + \frac{1}{\lambda(s, u, t)} [(s - u + m_K^2 - m_{D^*}^2)(-s(m_K^2 - m_\pi^2) + u(m_{D^*}^2 - m_\pi^2)) - t(u - m_K^2 + m_\pi^2)(s - m_{D^*}^2 + m_\pi^2)], \quad (14)$$

$$X = \frac{(u - m_K^2 + m_\pi^2)(u + s - t) - 2u(s - m_{D^*}^2 + m_\pi^2)}{\lambda(s, u, t)}, \quad (15)$$

$$Z = \frac{(s - u)^2 + (s - u)(m_K^2 - m_{D^*}^2) - (s + u)t + t(m_{D^*}^2 + m_K^2 - 2m_\pi^2)}{\lambda(s, u, t)}, \quad (16)$$

$$R_1(u, t) = (2u - t + m_{D^*}^2 - m_K^2 - 2m_\pi^2)/2, \quad (17)$$

and

$$R_2(t) = (m_{D^*}^2 + m_K^2 - t)/2. \quad (18)$$

The hadronic contributions to the form factors are then

expressed in terms of the double spectral functions ρ through

$$F(t) = \int_{s_1}^{s_m} \frac{ds}{s - m_D^2} \int_{u_1}^{u_m} \frac{du}{u - m_K^2} \rho_F(s, u, t) \quad (19)$$

TABLE I. Quantities which enter in the evaluation of the hadronic corrections to the semileptonic form factors at $t=0$ [see Eq. (23)]. The first column shows the cutoff values for the s and u integrations in the double dispersion integral, in units of GeV^2 .

$(s_m; u_m)$	F_{11}	F_{12}	F_{21}	F_{22}	F_{33}
(6.0; 1.7)	1.98×10^{-3}	6.32×10^{-5}	1.05×10^{-3}	-1.34×10^{-3}	2.00×10^{-3}
	$-i3.30 \times 10^{-3}$	$+i8.34 \times 10^{-5}$	$-i5.43 \times 10^{-3}$	$+i1.31 \times 10^{-4}$	$-i3.42 \times 10^{-3}$
(8.2; 3.6)	1.51×10^{-2}	-8.60×10^{-5}	1.34×10^{-2}	-5.50×10^{-3}	1.36×10^{-2}
	$-i8.39 \times 10^{-3}$	$+i6.10 \times 10^{-4}$	$-i1.15 \times 10^{-2}$	$+i1.07 \times 10^{-3}$	$-i7.99 \times 10^{-3}$
(15.0; 8.35)	6.50×10^{-2}	-2.76×10^{-4}	3.90×10^{-2}	-2.22×10^{-2}	4.58×10^{-2}
	$-i1.19 \times 10^{-2}$	$+i1.19 \times 10^{-3}$	$-i1.25 \times 10^{-2}$	$+i3.16 \times 10^{-3}$	$-i1.03 \times 10^{-2}$

TABLE II. t dependence of the contributions of the hadronic corrections to the form factors over the full kinematical range of the semileptonic decay $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$, with parameter values given in Eqs. (24)–(26). All entries have been multiplied by 100. An asterisk indicates that non-Landau singularities contribute.

t	$(s_m; u_m) = (6; 1.7)$			(8.2; 3.6)			(15; 8.35)		
	$A_1^{\text{had}}(t)$	$A_2^{\text{had}}(t)$	$V^{\text{had}}(t)$	$A_1^{\text{had}}(t)$	$A_2^{\text{had}}(t)$	$V^{\text{had}}(t)$	$A_1^{\text{had}}(t)$	$A_2^{\text{had}}(t)$	$V^{\text{had}}(t)$
0	0.359	−0.084	0.525	2.63	1.24	3.57	11.3	2.37	12.0
0.2	0.368	−0.151	0.545	2.82	1.32	3.88	12.1	2.46	12.9
0.4	0.394	−0.266	0.583	3.01	1.30	4.20	12.9	2.52	13.9
0.6	0.394	−0.441	0.603	3.24	1.26	4.63	14.3	2.48	15.6
0.8	0.398	−0.647	0.620	3.48	1.35	5.08	15.3	2.29	17.1
0.96	0.398	−0.819	0.627	3.71	1.53	5.52	*	*	*

for $F = A_1, A_2$, and V . The quantities s_1 and u_1 are the kinematical thresholds.

For $t \leq 0$ the integration region is bounded by the Landau curve, inside which all three internal momenta p_{D^*} , p_K , and p_π can be real and on the mass shell. For given $s \geq (m_{D^*} + m_\pi)^2$ and t the limits in u values are given by

$$u = \frac{1}{m_{D^*}^2} (-s(t - m_{D^*}^2 - m_K^2) + t(m_{D^*}^2 + m_\pi^2) - m_{D^*}^2(m_{D^*}^2 - m_K^2 - m_\pi^2) - m_K^2 m_\pi^2 \pm \lambda^{1/2}(t, m_{D^*}^2, m_K^2) \lambda^{1/2}(s, m_{D^*}^2, m_\pi^2)) . \quad (20)$$

For $t > 0$ special care has to be taken in order to incorporate non-Landau singularities (see Ref. [11]).

The double dispersion integrals, if extended to infinity in u and s , would lead to divergent expressions for the hadronic corrections. Actually, it turns out that the hadronic contribution to A_1 is linearly divergent in s_m , while those to A_2 and V diverge logarithmically. However, as mentioned in the Introduction, the composite nature of the hadrons leads to a damping of the ultraviolet contributions. We avoid these divergences by introducing sharp cutoffs s_m and u_m for the variables s and u , respectively. Actually, because of the dependence of the limits of the s and u integration on each other, as determined by the Landau curve, one cutoff would be sufficient, since for any fixed s the integration interval for u is finite.

The cutoffs s_m and u_m are determined by the hadronic excitation energies, since above them the single diagram (1) is no longer representative. We have thus parametrized s_m and u_m as

$$s_m = (m_D + \Delta)^2, \quad u_m = (m_{K^*} + \Delta)^2, \quad (21)$$

where Δ is conservatively varied in the range $0.6 \leq \Delta \leq 2$ GeV.

With a cutoff value s_m , the above-mentioned non-Landau singularities occur only for $t \gtrsim 4m_{D^*}^2/s_m$.

The point m_D^2 is always outside the integration interval of s , but $m_{K^*}^2$ is not always outside that of u . We therefore take into account the finite width of the K^* meson,

through the replacement

$$\frac{1}{u - m_{K^*}^2 + i\epsilon} \rightarrow \frac{u - m_{K^*}^2 - im_{K^*}\Gamma_{K^*}}{(u - m_{K^*}^2)^2 + (m_{K^*}\Gamma_{K^*})^2}, \quad (22)$$

where Γ_{K^*} is the full width of the K^* meson. The imaginary part of the hadronic corrections obtained in this way can be viewed as a consequence of a final-state interaction.

III. NUMERICAL RESULTS AND DISCUSSION

In Table I we present numerical values for the hadronic corrections to the different form factors of the $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$ decay. From the entries F_{ij} the hadronic corrections can be obtained through

$$A_i^{\text{had}} = \frac{G_D^* G_{K^*}^*}{4\pi} \sum_{j=1}^3 F_{ij} B_j, \quad (23)$$

with $A_3 \equiv V$, $B_3 \equiv W$, $F_{13} = F_{23} = F_{31} = F_{32} = 0$.

In the first row we have chosen $s_m = 6 \text{ GeV}^2$, $u_m = 1.7 \text{ GeV}^2$, corresponding to the continuum thresholds of the QCD sum-rule analysis [11]. In the second row we use the excitation energy $\Delta = 1 \text{ GeV}$, and in the last row, as a safe upper limit, $\Delta = 2 \text{ GeV}$. The hadronic corrections to the form factor A_1 are dominated by the B_1 contribution of the D^* semileptonic decay, whereas A_2 receives con-

TABLE III. Multiplicative factors representing the influence of the hadronic corrections on the polarization ratios and on the total decay rate. As in Table I, s_m and u_m represent the cutoff values in units of GeV^2 . R_{LT} is the ratio of the longitudinal and transversal polarizations including hadronic corrections, divided by the corresponding uncorrected quantity; $R_{+/-}$ is the analogous ratio for the relation between positive and negative helicities; and R_{tot} is the ratio between the total semileptonic decay rates including and not including hadronic corrections.

$(s_m; u_m)$	R_{LT}	$R_{+/-}$	R_{tot}
(6; 1.7)	1.01	1.01	1.02
(8.2; 3.6)	1.04	1.10	1.15
(15; 8.35)	1.19	1.49	1.77

TABLE IV. Quantities which enter in the evaluation of the hadronic corrections of the semileptonic form factors at $t=0$ of the decay $B \rightarrow D^* e \nu$ [analogous to Eq. (23)]. The first column shows the cutoff values for the s and u integrations in the double dispersion integral, in units of GeV^2 .

$(s_m; u_m)$	F_{11}	F_{12}	F_{21}	F_{22}	V
(34.6;6.8)	8.34×10^{-4} $-i3.52 \times 10^{-6}$	-9.27×10^{-6} $+i5.53 \times 10^{-8}$	1.44×10^{-3} $-i4.68 \times 10^{-6}$	-1.01×10^{-4} $+i1.15 \times 10^{-6}$	7.95×10^{-4} $-i3.58 \times 10^{-6}$
(39.4;9.0)	2.47×10^{-3} $-i3.56 \times 10^{-6}$	-4.02×10^{-5} $+i5.43 \times 10^{-8}$	3.70×10^{-3} $-i4.57 \times 10^{-6}$	-4.74×10^{-4} $+i1.17 \times 10^{-6}$	2.26×10^{-3} $-i3.66 \times 10^{-6}$
(53;16)	9.58×10^{-3} $-i3.66 \times 10^{-6}$	-2.14×10^{-4} $+i5.73 \times 10^{-8}$	1.12×10^{-2} $-i4.70 \times 10^{-6}$	-2.56×10^{-3} $+i1.06 \times 10^{-6}$	7.92×10^{-3} $-i3.84 \times 10^{-6}$

tributions proportional to B_1 and B_2 , with opposite signs and comparable magnitudes.

We have evaluated the form factors B_1, B_2 , and W of Eq. (3) by a sum-rule analysis. The procedure is close to that for D decays [11], and also the stability and parameter dependence turn out to be very similar to that of the corresponding ones for the decay $D \rightarrow \bar{K}^* e \nu$. The final results are

$$B_1(0)=0.7, \quad B_2(0)=0.8, \quad W(0)=1.1, \quad (24)$$

and the t dependence for all form factors is compatible with a pole fit

$$F(t)=F(0)/(1-t/m_p^2), \quad (25)$$

where $m_p=2.1$ GeV for B_2 and W and $m_p=2.9$ GeV for B_1 .

According to the definitions implied by Eqs. (4) and (5), the $D^* D \pi$ coupling constant G_{D^*} is obtained from G_{K^*} by replacing the strange quark by a charmed one. It is thus reasonable to assume

$$G_{D^*} \simeq G_{K^*}, \quad (26)$$

with a positive relative sign. From the K^* width we obtain $G_{K^*}^2/4\pi=2.5$, so that we may take

$$\frac{G_{D^*} G_{K^*}}{4\pi} = 2.5. \quad (27)$$

In Ref. [12] an even smaller value for G_{D^*} is obtained.

The t dependence of the hadronic corrections is partly due to the t dependence introduced by the structure of Fig. 1, and partly due to the t dependence of the form factors of the internal D^* decay [see Eq. (25)]. Since the two effects are superposed, the resulting t dependence is stronger than the one obtained in the pure quark case. We display the t dependence of the hadronic corrections to $A_1(t), A_2(t)$, and $V(t)$ in Table II, using the inputs given in Eqs. (24), (25), and (27).

In Table III we display the effect on measured quantities due to the hadronic corrections for cutoff values (in

GeV^2 units) given by $(s_m; u_m)=(6.0;1.7), (8.2;3.6)$, and $(15.0;8.35)$. The results of Ref. [11] have to be multiplied by the entries of Table III in order to include the effects of hadronic corrections. We observe that for the case $(6.0;1.7)$ the effects are completely negligible, and that even for the extremely large cutoff $s_m=15$ GeV^2 the effect of the hadronic corrections on the longitudinal to transversal polarization ratio is smaller than 20%. The main influence is on the decay rate, which is increased by 77%. The effect of the imaginary part is always completely negligible.

In Table IV we present results for the hadronic corrections to the semileptonic B decay $B \rightarrow D^* e \nu$. The amplitude has the same structure as that of Fig. 1, with the obvious substitutions $D \rightarrow B, D^* \rightarrow B^*, K \rightarrow D, K^* \rightarrow D^*$. Again, here we present the results for the excitation energy values $\Delta=0.6, 1$, and 2 GeV above the B and D^* masses. Since the D^* mass is practically at the $D\pi$ threshold, one could not exclude the occurrence of kinematical enhancements due to threshold effects. However, a comparison with Table I shows that the corresponding functions F_{ij} are in general even smaller than those of the D decay. Since the dimensionless form factors A_1, A_2 , and V for the B decay are expected to be of the same size as those of the D decay [13], our results show that hadronic corrections for the semileptonic B decay are indeed very small.

Summarizing, we remark that hadronic corrections cannot explain the existing discrepancy between the central value of the experimental results for the $D^+ \rightarrow \bar{K}^{0*} e^+ \nu$ decay and the theoretical result obtained from sum rules for the ratio of the longitudinal to the transversal polarization. Specifically, hadronic corrections cannot noticeably lower the form factor A_2 obtained in Ref. [11]. However, it can be remarked that the corrections obtained slightly move the polarization ratios towards a better agreement with experiment.

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