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Exclusive Semileptonic Decays of Heavy Mesons

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Abstract. Exclusive semileptonic decays of heavy mesons provide interesting information on systems consisting of quarks of unequal mass. We express the formfactors of the hadronic current in terms of relativistic bound state wave functions for which we take the solutions of a relativistic harmonic oscillator potential. The wave function overlap is determined by the quark mass dependent longitudinal momentum distribution and differs from results based on non relativistic wave functions. The semileptonic widths and lepton spectra are calculated using in addition nearest pole dominance for the momentum transfer dependence of the formfactors. We compare our results with recent experimental data. The formfactor calculation also allows an estimate of special nonleptonic transitions. From the CLEO results on $\bar{B}^0 \to \pi^+ \pi^-$ and $\bar{B}^0 \to D^{*+} + \pi^-$ we find for the corresponding Kobayashi-Maskawa matrix element ratio the limit $|V_{ub}/V_{cb}| \lesssim 0.3$.

I. Introduction

Semileptonic decays of hadrons have played and still play an important role for our understanding of the interplay of weak and strong interactions. The chiral $V-A$ symmetry of weak processes suggested many years ago [1] is now established also for heavy particle decays, quantitatively for τ-decay [2] and qualitatively for D and B-decays. The decay amplitudes are given by the product of the leptonic and a hadronic $V-A$ current. The spectra and rates for specific exclusive channels such as

$$D \to K e^+ \nu \qquad D \to K^* e^+ \nu$$

$$B \to D e^- \bar{\nu} \qquad B \to D^* e^- \bar{\nu}$$

are of particular interest. The corresponding matrix elements of the hadronic current are determined by the bound state properties of the initial and final mesons. Thus, exclusive semi-leptonic decays give valuable direct information on the internal structure of systems consisting of a heavy and a light quark. Also, any knowledge about these hadronic matrix elements is of direct importance in the estimate of prominent nonleptonic decays of heavy mesons.

Many attempts have been made to determine matrix elements of currents [3-10]. In the present work we will extend and improve a method proposed by Fakirov and Stech in their treatment of exclusive F and D-decays [5] which was recently used [11, 12] to analyse the new D-decay data of the Mark III collaboration [13]. The relevant meson formfactors are estimated with the help of relativistic quark wave functions in the infinite momentum frame. The relativistic treatment turns out to be rather essential. We quote the formfactors obtained (at $q^2=0$) and compare our calculation of lepton spectra and exclusive widths with the new experimental results on semileptonic D and B-decays [14, 15]. In a first application to nonleptonic B-decays into a charmless channel we extract a limit for the Kobayashi-Maskawa matrix element ratio $|V_{ub}/V_{cb}|$. An extensive compilation of results for nonleptonic D, F and B-decays will be given in a forthcoming paper.

II. Method and Results

The decay amplitudes for a 0^- meson I decaying into a 0^- meson X and leptons or into a 1^- meson X^* and leptons are determined by the current matrix elements

$$\langle X|j_\mu|I\rangle \quad \text{and} \quad \langle X^*|j_\mu|I\rangle \tag{1}$$

where j_μ stands for the appropriate $V-A$ quark current normalized by equal time commutation relations. From Lorentz invariance one finds the formfactor decomposition:

$$\langle X|j_\mu|I\rangle = \left(P_I + P_X - \frac{m_I^2 - m_X^2}{q^2}q\right)_\mu F_1(q^2) + \frac{m_I^2 - m_X^2}{q^2} q_\mu F_0(q^2) \tag{2}$$

with $q_\mu = (P_I - P_X)_\mu$ and $F_1(0) = F_0(0)$. $F_0(q^2)$ and $F_1(q^2)$ respectively denote longitudinal and transverse formfactors. In the expression for $\langle X^*|j_\mu|I\rangle$ four formfactors appear and the decomposition can be written in the form [12]

$$\langle X^*|j_\mu|I\rangle = \frac{2}{m_I + m_{X^*}} \varepsilon_{\mu\nu\rho\sigma} \varepsilon^{*\nu} P_I^\rho P_{X^*}^\sigma V(q^2) + i\left\{\varepsilon_\mu^*(m_I + m_{X^*}) A_1(q^2) - \frac{\varepsilon^* \cdot q}{m_I + m_{X^*}})(P_I + P_{X^*})_\mu A_2(q^2) - \frac{\varepsilon^* \cdot q}{q^2} 2m_{X^*} q_\mu A_3(q^2)\right\} + i\frac{\varepsilon^* \cdot q}{q^2} 2m_{X^*} q_\mu A_0(q^2)$$

$$A_3(0) = A_0(0). \tag{3}$$

Here $A_3(q^2)$ is an abbreviation for

$$A_3(q^2) = \frac{m_I + m_{X^*}}{2m_{X^*}} A_1(q^2) - \frac{m_I - m_{X^*}}{2m_{X^*}} A_2(q^2) \tag{4}$$

ε_μ denotes the polarization vector of the outgoing 1^- meson. Our task will be to estimate the invariant formfactors appearing in (2) and (3). Once they are known the exclusive decay rates and the lepton spectra can be calculated in a straightforward manner.

As to the dependence of the formfactors on q^2 it appears reasonable to assume nearest pole dominance [5]. For instance, the formfactor $F_1(q^2)$ in the $D \to K$ transition and the formfactor $V(q^2)$ in the $D \to K^*$ transition are expected to be dominated by the $F^*(2110)$ pole, and the formfactor $A_0(q^2)$ in the $D \to K^*$ transition should be dominated by the $F(1971)$ pole. We therefore take in these examples

$$D \to K\colon\ F_1(q^2) \simeq \frac{h_1}{1 - q^2/m_{F^*}^2},$$

$$D \to K^*\colon\ V(q^2) \simeq \frac{h_V}{1 - q^2/m_{F^*}^2}, \qquad A_0(q^2) \simeq \frac{h_{A_0}}{1 - q^2/m_F^2}. \tag{5}$$

Pole dominance, taken in this way, insures asymptotic (large q^2) current conservation. For $F_0(q^2)$ and $A_1(q^2)$, $A_2(q^2)$ the positions of 0^+ poles and 1^+ poles, respectively, are needed but are not known. However, approximate values are sufficient for our purpose. For the numerical calculations we use the mass values displayed in Table 1.

With pole dominated formfactors as in (5) the problem is now reduced to finding the values of the formfactors at $q^2 = 0$, i.e. the constants:

Table 1. Values of pole masses used in the numerical estimates

Current	$m(0^-)$ (GeV)	$m(1^-)$ (GeV)	$m(0^+)$ (GeV)	$m(1^+)$ (GeV)
$\bar{d}c$	1.87	2.01	2.47	2.42
$\bar{s}c$	1.97	2.11	2.60	2.53
$\bar{u}b$	5.27	5.32	5.99	5.71
$\bar{c}b$	6.30	6.34	6.80	6.73

$$h_0 = h_1, \quad h_V, \quad h_{A_1}, \quad h_{A_2}, \quad h_{A_3} = h_{A_0},$$

where h_{A_1}, h_{A_2}, and h_{A_3} are linearly related through Eq. (4). We call these factors h overlap factors. As we will see below they can be expressed as the overlap of initial and final internal meson wave functions. h_1 and h_{A_0} are the "charges" of a broken collinear symmetry at infinite momentum.

To proceed we describe the initial and final mesons as relativistic bound states of a quark q_1 and an anti-quark $\bar{q}_2$ in the infinite momentum frame (or equivalently on the null plane) [16, 9]

$$|\mathbf{P}, m, j, j_z\rangle = \sqrt{2}(2\pi)^{3/2} \sum_{s_1 s_2} \int d^3p_1 d^3p_2 \delta^3(\mathbf{P} - \mathbf{p}_1 - \mathbf{p}_2) \cdot \mathscr{S}_m^{j, j_z}(\mathbf{p}_{1T}, x, s_1, s_2) a_1^{s_1^+}(\mathbf{p}_1) b_2^{s_2^+}(\mathbf{p}_2)|0\rangle \tag{6}$$

where $P_\mu = (P_0, 0, 0, P)$ with $P \to \infty$. We suppressed colour indices. x denotes the fraction of the longitudinal momentum carried by the non spectator quark q_1, and $\mathbf{p}_{1T}$ its transverse momentum:

$$x = p_{1z}/P, \qquad \mathbf{p}_{1T} = (p_{1x}, p_{1y}).$$

The function $\mathscr{S}_m$ describes the internal wave function of a meson of mass m for two quark constituents. Since we do not consider any extra gluon component, these effective quarks carry a gluon cloud and thus have constituent masses. The normalization used here is

$$\{a^{s'}(\mathbf{p}'), a^{s+}(\mathbf{p})\} = \delta_{s's} \delta^3(\mathbf{p}' - \mathbf{p}) \cdot \sum_{s_1, s_2} \int |\mathscr{S}_m(\mathbf{p}_T, x, s_1, s_2)|^2 d^2p_T dx = 1 \tag{7}$$

giving

$$\langle \mathbf{P}'|\mathbf{P}\rangle = 2P^0(2\pi)^3 \delta^3(\mathbf{P}' - \mathbf{P}).$$

By expressing the current j_μ in terms of annihilation and creation operators, we obtain from (1) (6) and comparing with (2) (3) the formfactors in terms of the meson wave functions $\mathscr{S}_m$. For $q^2 = 0$ it is in fact sufficient to consider the space intregrals of the cur-

Table 2. Partial decay rates for Cabibbo allowed and Cabibbo suppressed ($\sin\theta_c=0.225$) semileptonic D-decays and preliminary experimental numbers [18]

ω (GeV)	$\Gamma(D\to K)$ ($10^{10}\,\mathrm{s}^{-1}$)	$\Gamma(D\to K^*)$ ($10^{10}\,\mathrm{s}^{-1}$)	$\Gamma(D\to\pi)$ ($10^{10}\,\mathrm{s}^{-1}$)	$\Gamma(D\to\rho)$ ($10^{10}\,\mathrm{s}^{-1}$)	$\Gamma(D\to K,K^*,\pi,\rho)$ ($10^{10}\,\mathrm{s}^{-1}$)
0.350	7.56	7.73	0.63	0.53	16.45
0.400	8.26	9.53	0.73	0.70	19.22
0.500	9.64	13.42	0.93	1.08	25.07
Experiment	7.8 ± 1.1	7.6 ± 1.6	–	–	$\Gamma(D\to X e\nu)$ inclusive 18.6 ± 2.1

rent components in (1). We find

$$h_1=h_0=\int d^2p_T\int_0^1 dx(\mathcal{S}_X^*(\mathbf{p}_T,x)\,\mathcal{S}_I(\mathbf{p}_T,x))$$

$$h_{A_0}=h_{A_3}=\int d^2p_T\int_0^1 dx(\mathcal{S}_{X^*}^{*1,0}(\mathbf{p}_T,x)\,\sigma_z^{(1)}\,\mathcal{S}_I(\mathbf{p}_T,x)). \qquad (8)$$

$\sigma_z^{(1)}$ is a Pauli matrix acting on the spin indices of the decaying quark (q_1). It is seen from (8) that $F_1(0)=A_0(0)=1$ holds in the formal limit of a strict collinear symmetry combining spin and flavour, i.e. an $SU(4)$ symmetry acting on two spin states and two appropriate quark flavours. The space integrals of the corresponding current components are the generators of this collinear spin-flavour group. The remaining formfactors at zero momentum transfer contain explicitly the masses $m_{q_1(I)}$ and $m_{q_1(X)}$ of the non-spectator quarks participating in the quark decay process. With the abbreviation

$$J=\sqrt{2}\int d^2p_T\int_0^1\frac{dx}{x}(\mathcal{S}_{X^*}^{*1,-1}(\mathbf{p}_T,x)\,i\,\sigma_y^{(1)}\,\mathcal{S}_I(\mathbf{p}_T,x)) \qquad (9)$$

one obtains

$$h_V=\frac{m_{q_1(I)}-m_{q_1(X^*)}}{m_I-m_{X^*}}J$$
$$h_{A_1}=\frac{m_{q_1(I)}+m_{q_1(X^*)}}{m_I+m_{X^*}}J \qquad (10)$$

and from (4)

$$h_{A_2}=\frac{m_I+m_{X^*}}{m_I-m_{X^*}}h_{A_1}-\frac{2m_{X^*}}{m_I-m_{X^*}}h_{A_0}. \qquad (11)$$

It remains to find an ansatz for the meson wave functions $\mathcal{S}_m(\mathbf{p}_T,x,s_1,s_2)$. Since the spectator antiquark and the π and K-mesons have mass values comparable to the average internal quark momenta, a relativistic treatment is necessary. Little is known about relativistic wave functions with quarks of unequal masses. We take the solution* of a relativistic scalar harmonic oscillator potential [16, 17]. With a factorization of spin and orbital motion we find for the orbital part

$$\mathcal{S}_m(\mathbf{p}_T,x)=N_m\sqrt{x(1-x)}\exp(-\mathbf{p}_T^2/2\omega^2)\cdot\exp\left(-\frac{m^2}{2\omega^2}\left(x-\frac{1}{2}-\frac{m_{q_1}^2-m_{q_2}^2}{2m^2}\right)^2\right). \qquad (12)$$

N_m is a normalization factor (see (7)). The difference of the square of the constituent quark masses gives an important shift of the x-distribution which is different for the different mesons. The quark mass values used in the numerical estimates are $m_u=m_d=0.35$, $m_s=0.55$, $m_c=1.7$, $m_b=4.9$ GeV. Equation (12) contains the parameter ω which determines the average transverse quark momentum:

$$\langle\mathbf{p}_T^2\rangle=\omega^2. \qquad (13)$$

From flavour independence of the QCD forces the confining potential, and thus ω, is not expected to be much different for the various mesons. Even though at least the radius of the π-meson differs somewhat from the radius of the K-meson, we take – somewhat optimistically – ω to be the same for all mesons with the same spectator quark. To see the dependence on this parameter we give our results for $\omega=0.35$, 0.40 and 0.50 GeV. The resulting partial widths for Cabibbo allowed and Cabibbo suppressed D-decays are displayed in Table 2 together with the experimentally determined numbers [18]. It is seen that with $\omega\simeq0.40$ GeV the experimental data are well reproduced. The corresponding theoretical lepton spectra are shown in Fig. 1a and compared with the DELCO data [19] in Fig. 1b.

In the same way, the decay widths and spectra for semileptonic B-decays can be predicted. The results are shown in Table 3 and Fig. 2. Here we took for the B-meson lifetime $\tau_B=(1.2\pm0.16)\times10^{-12}$ s and for the Kobayashi-Maskawa matrix element $|V_{cb}|=0.05$. Again, agreement with the data can be claimed. The spectra in Figs. 1 and 2 are plotted for

* Derivation and details are left to a separate publication

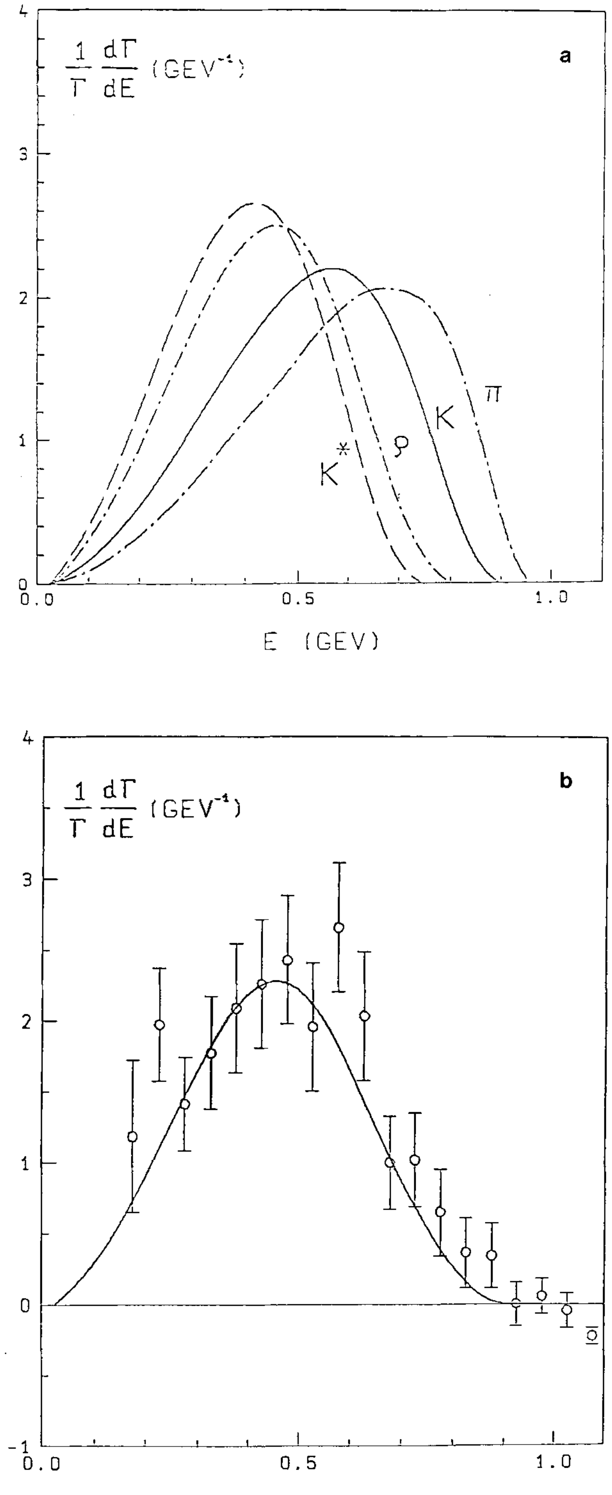

Fig. 1. **a** Normalized theoretical spectra for semileptonic D-decays to K, K^*, π and ρ mesons ($\omega = 0.400$ GeV). **b** Theoretical spectrum for the semileptonic decay of D-mesons to K and K^* mesons. The experimental points are DELCO data points for the inclusive decay. The theoretical curve is a D-meson restframe spectrum and thus not corrected for the Lorentzboost inherent in the DELCO data

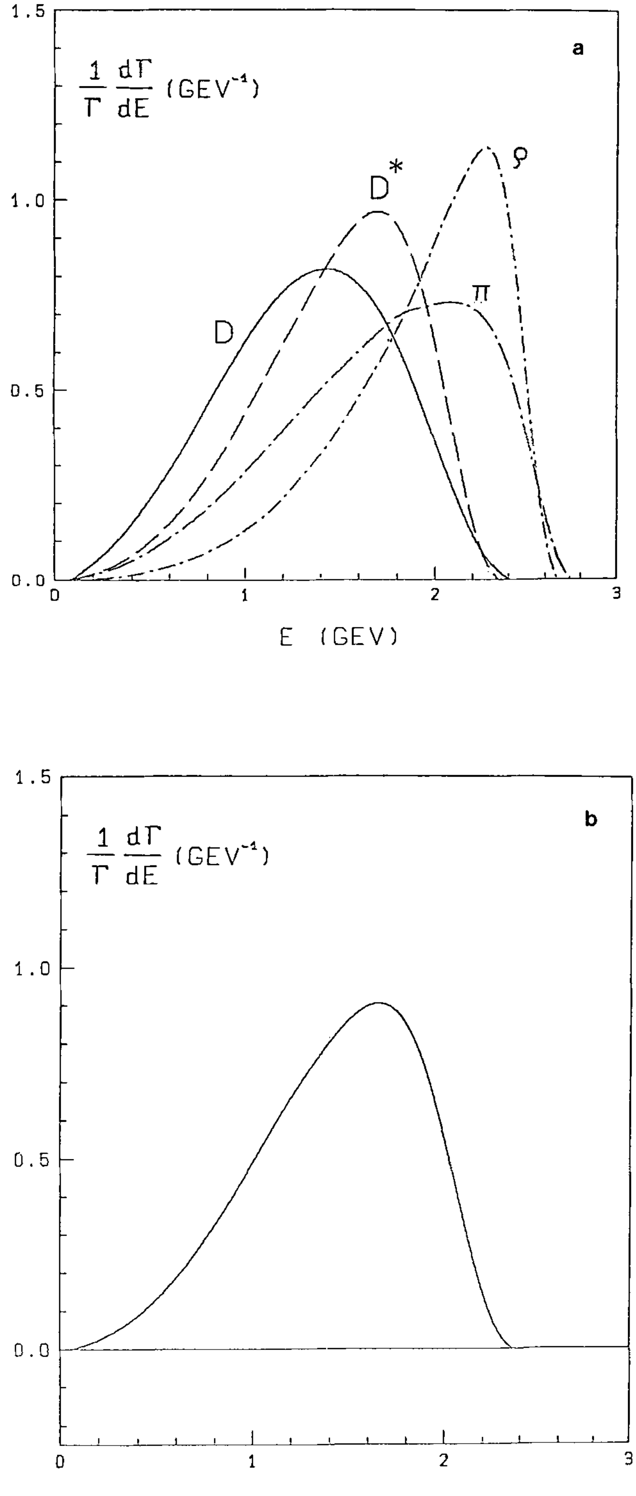

Fig. 2. **a** Normalized theoretical spectra for semileptonic B-decays to D, D^*, π and ρ mesons ($\omega = 0.400$ GeV). **b** Theoretical spectrum for the semileptonic decay of B-mesons to D and D^* mesons

Table 3. Partial decay rates for semileptonic B-decays to charm and charmless states. For the comparison with experiment [15] we take $|V_{cb}|=0.05$

ω (GeV)	$\Gamma(B\to D)$ $(10^{12}\,s^{-1})$	$\Gamma(B\to D^*)$ $(10^{12}\,s^{-1})$	$\Gamma(B\to\pi)$ $(10^{12}\,s^{-1})$	$\Gamma(B\to\rho)$ $(10^{12}\,s^{-1})$	$\Gamma(B\to D, D^*)$ $(10^{10}\,s^{-1})$
0.350	$8.01\,\lvert V_{cb}\rvert^2$	$20.1\,\lvert V_{cb}\rvert^2$	$6.32\,\lvert V_{ub}\rvert^2$	$18.7\,\lvert V_{ub}\rvert^2$	7.03
0.400	$8.08\,\lvert V_{cb}\rvert^2$	$21.9\,\lvert V_{cb}\rvert^2$	$7.43\,\lvert V_{ub}\rvert^2$	$26.1\,\lvert V_{ub}\rvert^2$	7.50
0.500	$8.26\,\lvert V_{cb}\rvert^2$	$24.9\,\lvert V_{cb}\rvert^2$	$9.99\,\lvert V_{ub}\rvert^2$	$42.5\,\lvert V_{ub}\rvert^2$	8.29
Experiment	–	–	–	–	$\Gamma(B\to X e \nu)$ inclusive 9.4 ± 1.3

Table 4. Formfactors at $q^2=0$ (overlap factors) for $\omega=0.400$ GeV and in parenthesis for $\omega=0.500$ GeV

Process	$h_0=h_1$	h_V	h_{A_1}	h_{A_2}	$h_{A_3}=h_{A_0}$
$D\to K$	0.76 (0.82)				
$D\to K^*$		1.27 (1.53)	0.88 (1.07)	1.15 (1.52)	0.73 (0.81)
$D\to\pi$	0.69 (0.78)				
$D\to\rho$		1.23 (1.55)	0.78 (0.98)	0.92 (1.27)	0.67 (0.77)
$B\to D$	0.69 (0.70)				
$B\to D^*$		0.71 0.76)	0.65 (0.70)	0.69 (0.76)	0.62 (0.65)
$B\to\pi$	0.33 (0.39)				
$B\to\rho$		0.33 (0.42)	0.28 (0.36)	0.28 (0.37)	0.28 (0.35)

$\omega=0.40$ GeV. These spectra and the ratios

$$\Gamma(I\to X^*)/(\Gamma(I\to X)+\Gamma(I\to X^*))$$

are not very sensitive to the precise value of ω.

In Table 4 we finally present the overlap factors for the exclusive decays discussed in this paper for $\omega=0.40$ GeV. The values given in parenthesis are for $\omega=0.50$ GeV. The overlap factors are decisive for all calculations of exclusive decay widths. In earlier articles [5, 20] the symmetry limes $h_1=h_{A_0}=1$ was taken and h_V, h_{A_2} assumed to be small. The total semileptonic branching ratio was predicted correctly but with $I\to X$ dominating over $I\to X^*$ in disagreement with recent findings. The calculation of the overlap factors as presented here clarifies this issue. Some values differ significantly from the symmetry limes. The calculated numbers give transition rates in good agreement with presently available data.

We remark here that a calculation of the overlap factors using a non-relativistic harmonic oscillator wave function is not consistent with our results. For instance, for h_1 one would obtain

$$h_1 \simeq \left(\frac{2m_X m_I}{m_X^2+m_I^2}\right)^{1/2}$$

which is certainly not correct for small masses m_X. The reason for this failure is that in a non-relativistic treatment the spectrum condition $0\leqq x\leqq 1$ is not fulfilled. Therefore, the estimated $K-\pi$ formfactor $F_1(0)$, for example, is too small. Non-relativistic wave functions are reliable only if the mesons and both constituent quarks are heavy compared to the average internal momentum.* In the relativistic treatment and with $\omega=0.40$ GeV we obtain for the $K-\pi$ formfactor $F_1(0)=h_1=0.992$ in agreement with estimates of Leutwyler and Roos [9].

The ratio $\Gamma(B\to D^*)/(\Gamma(B\to D)+\Gamma(B\to D^*))\simeq 0.73$ obtained here (Table 3) agrees with an estimate by Suzuki [21] based on free quark decay. The experimental value [15] is 0.85 ± 0.32. In Suzuki's approach one expects, however, the same value also for the ratio

$$\Gamma(D\to K^*)/(\Gamma(D\to K)+\Gamma(D\to K^*))$$

whereas we find (Table 2) the value 0.53 compatible with the recent experimental determination [18] giving 0.49 ± 0.12.

The lepton spectra displayed in Fig. 1b and 2b are similar in form to the ones obtained by Altarelli et al. [22] for the *inclusive* quark decay process. This inclusive B-decay spectrum has advantageously been used to extract limits on the ratio $|V_{ub}/V_{cb}|$ [23] which is of outstanding importance for particle physics. The detailed information on the exclusive B-decay lepton spectra presented here can now be of

* In [7] and [10] non-relativistic "mock wave functions" with unphysically large π and K-masses are employed. They lead to an acceptable $K-\pi$ formfactor but are hard to justify

additional help for an experimental determination of this quantity. We do not perform such an analysis in this article since a precise consideration of the experimental conditions would be needed for that purpose.

The overlap factors of Table 4 are of immediate use for certain exclusive nonleptonic decays - namely energetic two-body decays. Applying the method of [11, 12] we find

$$\Gamma(\bar{B}^0 \to \pi^+ \pi^-) \simeq 1.26\, a_1^2 |V_{ub}/0.05|^2 (h_1^{B\to\pi})^2\, 10^{10}\, \mathrm{s}^{-1}$$
$$\Gamma(\bar{B}^0 \to D^{*+} \pi^-) \simeq 0.79\, a_1^2 |V_{cb}/0.05|^2 (h_{A_0}^{B\to D^*})^2\, 10^{10}\, \mathrm{s}^{-1}. \quad (14)$$

a_1 is a coefficient of order 1 present in the effective Hamiltonian relevant for nonleptonic B-decays. From the recent CLEO results [15, 24]

$$BR(\bar{B}^0 \to \pi^+ \pi^-) \lesssim 0.02\,\%,$$
$$BR(\bar{B}^0 \to D^{*+} \pi^-) \simeq (2.1 \pm 1.1)\,\%$$

and Table 4 one obtains - without correction for final state interaction - $|V_{ub}/V_{cb}| \lesssim 0.21$. A solid theoretical error estimate for this ratio cannot be given. However the success of the model in describing semileptonic and nonleptonic D-decays and in particular also Cabibbo suppressed D-decays suggests that a 50% increase of the above number for $|V_{ub}/V_{cb}|$ constitutes a conservative limit: $|V_{ub}/V_{cb}| \lesssim 0.3$. Perhaps a point of concern is the magnitude for a_1 obtained from (14) taking $|V_{cb}| = 0.05$ and $BR(\bar{B}^0 \to D^{*+} \pi^-) = 2\%$: one finds $a_1 \simeq 2.3$ instead of the expected value $a_1 \simeq 1.1$ [11, 12]. The uncertainty in the overlap factor should not be more than $\simeq 15\%$. However, it is conceivable that the branching ratio for $\bar{B}^0 \to D^{*+} \pi^-$ will come down to $\approx 1\%$ and that also $|V_{cb}|$ is somewhat larger (say 0.06) than estimated from the inclusive decay. Only hesitatingly we would accept the second way out: a sizeable annihilation contribution for this energetic two-body B-decay.

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