Spectra of Exclusive Semi-Leptonic Decays of B-meson in the Covariant Oscillator Quark Model

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The spectra and form factors of exclusive semi-leptonic decays of B-meson are analyzed, taking account of confined effects of quarks by the Covariant Oscillator Quark Model. The predicted $B \to (D^*, D)\bar{l}\nu_l$ spectra with the conventional value of $V_{cb}$ are fit well to the high-precision experiment. It is also shown the values of $V_{cb}$ and $V_{ub}$ obtained through decay widths for the $B \to (D, D^*, \rho)\bar{l}\nu_l$ processes are consistent with the presently accepted ones.

§1. Introduction

The exclusive semi-leptonic decay has been one of the important topics of high energy physics for many years, however it has been a difficult task to explain its spectra quantitatively. They are largely affected by the confined effects of quarks. Especially in the decays of B-mesons the final mesons generally make highly relativistic motions, making the situation more complex. Among many experimental studies the spectra of $B \to D^*\bar{l}\nu_l$ and $B \to D\bar{l}\nu_l$ decays are obtained with high precisions, of which analysis has been one of the main interests in the heavy quark effective theory (HQET). In HQET all generally independent form factors, appearing in the effective meson transition current $J_{\mu}^{B \to D^*/D}$, are represented by one universal form factor (FF) function (Isgur-Wise function $\xi(\omega)$), thus leading to various FF-relations among them. The value of $\xi(\omega)$ at zero-recoil point is to be unity, $\xi(1) = 1$, in the heavy quark mass limit $m_Q \to \infty$, reflecting the conserved charge of heavy quark symmetry (HQS). However, HQET and/or HQS themselves are not able to predict the concrete form of $\xi(\omega)$, and accordingly it cannot describe the FF function and the decay spectra in all regions of $q^2$. For this it is, in principle, necessary to know covariant wave functions (WF) of mesons concerning both spin and space-time variables, and presently we are required to resort to some models with a covariant framework. The FF function is obtained as an overlapping of initial and final state WF.

In this work we shall study the FF's and spectra of semi-leptonic B-meson decays, using the Covariant Oscillator Quark Model (COQM) in order to estimate the confined effects of quarks. The COQM has a long history of development, and its origin may be traced back to the bilocal theory by Yukawa. The general framework of COQM is called the boosted LS-coupling scheme, and the hadron WF, being ten-
in $\tilde{U}(4) \times O(3,1)$-space, reduce to those in $SU(2)_{\text{spin}} \times O(3)_{\text{orbit}}$-space in the non-relativistic quark model in the hadron rest frame. The spinor and space-time portions of WF satisfy separately the respective covariant equations, the Bargmann-Wigner (BW) equations for the former and the covariant oscillator equation for the latter. The concrete form of meson WF has been determined completely through the analysis of mass spectra. Their validity seems to be shown, to some extent, phenomenologically by their applications to various dynamical processes, such as the electro-magnetic FF and the radiative decay of light quark mesons. Recently we have applied them to general semi-leptonic decays of mesons and baryons. It is especially interesting that for the $B \to D^*/D^0 l \bar{\nu}_l$ decays completely the same FF relations as in HQET are derived in COQM. The physical origin of obtaining the same FF relations is the use of the BW spinor functions. We have argued in our previous work that these BW functions are also implicitly supposed in HQET.

According to the analysis of meson mass spectra, there seems to be a sufficient phenomenological reason for the validity of BW equations also in the light quark meson system. So we shall make the similar analysis of the process $B \to \rho l \bar{\nu}_l$, (which is out of the scope of HQET by itself) as well as $B \to D/D^* l \bar{\nu}_l$ in this work.

§2. Meson wave functions

In COQM all non-exotic $q\bar{q}$-mesons are described unifiedly by bi-local fields $\Phi_A^B(x_1, x_2)$, where $x_1, x_2$ is a space-time coordinate of constituent quark (anti-quark), $A = (a, \alpha)$ ($B = (b, \beta)$) describing its flavor and covariant spinor. Here we write only the (positive frequency part of) relevant ground state fields.

$$\Phi_A^B(x_1, x_2) = e^{iP \cdot X} U(P)_A^B f(x_2 - x_1), \quad (1)$$

where $U$ and $f$ are the covariant spinor and internal space-time WF, respectively, satisfying the BW and oscillator wave equations. The $x_\mu$ ($X_\mu$) is the relative (CM) coordinate, $x_\mu \equiv x_1 - x_2$ ($X_\mu \equiv (m_1 x_1 + m_2 x_2)/(m_1 + m_2)$; $m_i$'s being quark masses). The $U$ is given by

$$U(P) = \frac{1}{2 \sqrt{2}} [(\gamma_5 P_\mu(v) + i \gamma_\mu V_\mu(v))(1 + iv \cdot \gamma)], \quad (2)$$

where $P_\mu(V_\mu)$ represents the pseudoscalar (vector) meson field, and $v_\mu \equiv P_\mu(M)/P_\mu(M)$ being four momentum (mass) of meson. The $U$, being represented by the direct product of quark and anti-quark Dirac spinor with the meson velocity, is reduced to the

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***) Application of covariant oscillator function to semi-leptonic decays was done firstly in ref. 9. The preliminary result of this work was presented in refs. 10.

**** In the case of light-and heavy-quark meson system the $I$-function (taking $m_Q \to \infty$) is identical to the Isgur-Wise function $\xi(\omega)$.
non-relativistic Pauli-spin function in the meson rest frame. The $f$ is given by

$$f(x_\mu; P) = \frac{\beta}{\pi} e^{-\frac{2}{\pi}(x_\mu^2 + \frac{2x_\mu P_\mu}{M^2})^2}, \quad \beta = \sqrt{\frac{\mu K}{\pi}},$$  \hspace{1cm} (3)$$

where $\mu$ is the reduced mass, and $K$ is the spring constant of oscillator potential.

We treat our problem in the following two cases of parameters, $m'_q$ and $K$.

Case A: The $m'_q$'s are simply determined by $M'_V = m_q + m_{\bar{q}}$, $M'_V$'s being the mass of relevant vector mesons, $B^*$, $D^*$ and $\rho$. The $K$ is supposed to be universal, independently of flavor-contents of mesons, and determined from the Regge slope of $\rho$ meson trajectory, $\Omega^{\exp} = 1.14$ GeV, by a relation $\Omega = \sqrt{32m_K}$. In this case the mixing of ground 1S-states with excited 2S-states is shown to be a few percents (the less) for $\rho$ ($D$ or $D^*$ and $B$) in the amplitudes, and thus its effects seem to be negligible.

The actual values of $m_q$'s and the $\beta$ for the respective systems are collected in Table I. The “size” of wave functions $\beta^{-1}$ seem to be almost equal in case B.

Table I. The adopted values of quark masses $m_q$'s and of inverse sizes $\beta$'s. In Case A: $K = 0.106$ GeV$^3$ is taken to be universal. In Case B: $K$ is determined from mass spectra as $K = 0.0979$, 0.0679 and 0.0619 GeV$^3$, respectively, for $\rho$, $D(D^*)$ and $B$ mesons. In Case B the size of mesons becomes almost equal.

|       | $m_u$  | $m_c$  | $m_b$  | $\beta_q$ | $\beta_{D/D^*}$ | $\beta_B$ |
|-------|--------|--------|--------|------------|-----------------|------------|
| Case A | 0.384 GeV | 1.62 GeV | 4.94 GeV | 0.143 GeV$^2$ | 0.181 GeV$^2$ | 0.194 GeV$^2$ |
| Case B | 0.400 GeV | 1.70 GeV | 5.00 GeV | 0.140 GeV$^2$ | 0.148 GeV$^2$ | 0.151 GeV$^2$ |

§3. Effective weak currents and reduced form factor function

Our effective action for weak interactions of mesons with W-boson is given by

$$S_W = \int d^4x_1d^4x_2\langle \Phi_{F,P'}(x_1,x_2)i\gamma_\mu(1 + \gamma_5)\Phi_{I,P}(x_1,x_2)\rangle W_{\mu,q}(x_1),$$  \hspace{1cm} (4)$$

where we have denoted the interacting (spectating) quarks as 1(2). (the KM matrix elements and the coupling constant are omitted.) This is obtained from consideration of Lorentz covariance, supposing the quark current with the standard $V - A$ form. In Eq.(4) $\Phi_{I,P}$ ($\Phi_{F,P'}$) denotes the initial (final) meson with the definite four momentum $P_\mu$ ($P'_\mu$), and $q_\mu$ is the momentum of W-boson. The $\Phi$ is the Pauli-conjugate of $\Phi$ defined by $\Phi \equiv -\gamma_4\Phi^\dagger\gamma_4$ and $\langle \rangle$ represents the trace of Dirac spinor indices. Our relevant effective currents $J^I_\mu(X)_{P',P}$ are ob-

![Fig. 1. I-functions of $B \rightarrow D^*$, $B \rightarrow D$ and $B \rightarrow \rho$ transitions, are denoted by solid, dashed and dotted lines, respectively. The thick (thin) line corresponds to the case A(B).](image-url)
tained by identifying the above action with
\[ S_W = \int d^4X J_\mu(X) p^\nu p W_\mu(X) q. \]

Then \( J_\mu(X = 0) p^\nu p \equiv J_\mu \) is explicitly given as
\[ J_\mu = I_n^{GB}(\omega) \sqrt{MM'} \]
\[ [\bar{P}_s(v') P_s(v)(v + v')_\mu + \bar{V}_s(v') P_s(v)(\epsilon_{\mu\lambda\alpha\beta} v'_\alpha v_\beta - \delta_{\lambda\mu}(\omega + 1) - v_\lambda v'_\mu)], \]

where \( \omega = -v \cdot v' \). The \( I_n^{GB}(\omega) \) is the overlapping of the initial and final space-time wave functions, which describes the confined effects of quarks, and is given by
\[ I_n^{GB}(\omega) = \frac{4 \beta \beta'}{\beta + \beta'} \frac{1}{\sqrt{C(\omega)}} \exp(-G(\omega)); \quad C(\omega) = (\beta - \beta')^2 + 4 \beta \beta' \omega^2 \]
\[ G(\omega) = \frac{m_n^2}{2C(\omega)} \left[ (\beta + \beta') \left( \left( \frac{M}{M_s} \right)^2 + \left( \frac{M'}{M'_s} \right)^2 - 2 \frac{M M'}{M s M'_s} \omega \right) \right. \]
\[ + \left. 2 \left( \beta' \frac{M}{M_s} \right)^2 + \beta \left( \frac{M'}{M'_s} \right)^2 \right] (\omega^2 - 1), \] 

where \( m_1 + m_2(m_1' + m_2') \), of the initial (final) meson system. The actual forms of the relevant I-functions are drawn in Fig. 1, which are almost common in \( B \to D^*, D \) and \( \rho \) transitions. However, the kinematically allowed maximum value \( \omega_{\text{max}} \) of \( \omega \), 3.51, in \( B \to \rho \) transition is much larger than those 1.50(1.59) in \( B \to D^* \) (\( B \to D \)), and the corresponding value of \( I(\omega_{\text{max}}) \) is much smaller for the former than for the latter.

If we identify \( M(M') \) with \( M_s(M'_s) \), the \( G(\omega) \), Eq.(8), becomes simple as \( G(\omega) = m_n^2(\beta + \beta')(\omega - 1)/C(\omega) \). Moreover, in the \( m_Q \to \infty \) limit the size of \( B \) and \( D(D^*) \) mesons becomes equal, that is, \( \beta_B = \beta_{D/D^*} \equiv \beta_{\infty} \). Then the I-function of \( B \to D/D^* \) transitions takes the form, \( I_{\infty}(= \xi(\omega)) = 1/\omega \exp[-m_n^2(\omega - 1)/(2\beta_{\infty} \omega)] \), which has the property at zero-recoil, \( I_{\infty}(\omega = 1) = 1 \), similarly as the \( \xi(\omega) \). The actual values of \( I(1) \) in \( B \to D \) and \( B \to D^* \) transitions are, respectively, 0.984(0.999) and 0.986(1.000) for case A(B).
§4. Form factors and Decay spectra

The invariant FF’s of \( B \to D^*/D \) transitions are defined as:

\[
\langle D^*(P', \epsilon)|J_\mu|B(P)\rangle = \frac{2\epsilon_\mu\lambda_\alpha\beta}{M + m_{D^*}}\bar{v}_\lambda P_\alpha' P_\beta V_{D^*}^{(q^2)}(q^2) - (M + m_{D^*})\bar{v}_\mu A_{D^*}^{(q^2)}(q^2)
\]

\[
= -\frac{\bar{q} \cdot q}{M + m_{D^*}}(P + P')_\mu A_{D^*}^{(q^2)}, \quad \langle D(P')|J_\mu|B(P)\rangle = F_1^{D}(q^2)(P + P')_\mu,
\]

(9)

neglecting the terms proportional to \( q_\mu \), which are irrelevant in the massless lepton approximation. Comparing Eq.(9) with our effective currents Eq.(6) leads to the FF’s represented by \( I \)-function as

\[
V_{D^*} = A_{D^*}^{(q^2)} = \frac{A_{D^*}^{(q^2)}}{1 + q^2/(M + m_{D^*})^2} = \frac{M + m_{D^*}}{2\sqrt{Mm_{D^*}}} I_n^{cb}, \quad F_1^{D} = \frac{M + m_{D^*}}{2\sqrt{Mm_{D^*}}} I_n^{cb} \cdot (10)
\]

In \( B \to \rho \) transition the FF’s, defined similarly as in Eq.(9), are represented by

\[
V^\rho = A_{D^*}^{(q^2)} = \frac{A_{D}^{(q^2)}}{1 + q^2/(M + m_{\rho})^2} = \frac{M + m_{\rho}}{2\sqrt{Mm_{\rho}}} I_n^{cb}(\omega). \quad (11)
\]

These FF relations are the same as in \( B \to D^* \) and \( B \to \rho \) transitions, according to common use of BW spinor function. The actual \( Q^2(= -q^2) \) dependence of relevant FF’s are given in Fig. 2.

Our theoretical spectra of \( B \to Dl\nu_l \) and \( B \to Vl\nu_l \ (V = D^*, \rho) \) decays are obtained from the effective currents (6) as

\[
\frac{d\Gamma_{B \to D}}{dq^2} = |V_{cb}|^2 (I_n^{cb})^2 \frac{G_F^2 m_B^2}{96\pi^3 M_B} \sqrt{\omega^2 - 1} \sqrt{\omega^2 - 1} (M_B + m_D)^2,
\]

\[
\frac{d\Gamma_{B \to V}}{dq^2} = |V_{cb}|^2 (I_n^{cb})^2 \frac{G_F^2 m_V^2}{96\pi^3 M_B} \sqrt{\omega^2 - 1} \sqrt{\omega^2 - 1} [4\omega q^2 + (\omega + 1)(M_B - m_V)^2],
\]

(12)

where \( V_{cb} \)’s are the relevant Kobayashi-Maskawa matrix elements \( V_{KM} \), (our only free parameters,) and \( G_F \) is the Fermi constant (we adopt the value \( 1.166 \times 10^{-5} \text{GeV}^{-2} \)). The best fits to the experimental spectra, (a) \( |V_{cb}|I(\omega) \) and (b) \( d\Gamma/dQ^2 \), are shown, in Fig.3 for \( B \to D^* \) decay and in Fig.4 for \( B \to \rho \) decay. For reference we have also shown the results with \( I \)-function taken as unity, which correspond to “free quark decay”\(^{[3]}\) in Figs. 3(b) and 4(b). The \( V_{cb} \)-values thus determined are given in Table II, where the combined values of \( V_{cb} \) for the respective processes are also given.

\(^{[3]}\) A similar formula for \( B \to \pi \) transition as for \( B \to D \) may be also applicable. However, it may not be effective because no considerations on the property of \( \pi \) as Nambu-Goldstone boson are given in our present framework.

\(^{[3]}\) Here the combined value of \( V_{cb} \) in Table II is used.
Table II. The values of $V_{cb}$ obtained from the best fit to the experimental spectra in $B \rightarrow D^* l \bar{\nu}_l$ and $B \rightarrow D l \bar{\nu}_l$ decays. The second errors are the systematic ones for $|V_{cb}| F(1)$ (including the error of B-life time) quoted from ref.12) and ref.13) for the respective processes.

|          | case A               | case B               | combined            |
|----------|----------------------|----------------------|---------------------|
| $B \rightarrow D^* l \bar{\nu}_l$ | $(3.88 \pm 0.10 \pm 0.20) \times 10^{-2}$ | $(3.89 \pm 0.10 \pm 0.20) \times 10^{-2}$ | $(3.89 \pm 0.10 \pm 0.20) \times 10^{-2}$ |
| $B \rightarrow D l \bar{\nu}_l$   | $(4.11 \pm 0.14 \pm 0.46) \times 10^{-2}$ | $(4.15 \pm 0.14 \pm 0.46) \times 10^{-2}$ | $(4.13 \pm 0.14 \pm 0.46) \times 10^{-2}$ |

Fig. 3. Comparison of theory and experiment$^{12}$ for decay spectra in $B \rightarrow D^* l \bar{\nu}_l$, (a) $|V_{cb}| \omega$ and (b) $d\Gamma/dQ^2(\text{ps}^{-1}\text{GeV}^{-2})$. A thick solid (dashed) line corresponds to the case A(B). A thin dashed line in Fig.(b) is the one in case of “free quark decay”.

Fig. 4. Comparison of theory and experiment$^{13}$ for decay spectra in $B \rightarrow D l \bar{\nu}_l$, (a) $|V_{cb}| \omega$ and (b) $d\Gamma/dQ^2(\text{ps}^{-1}\text{GeV}^{-2})$. A thick solid (dashed) line corresponds to the case A(B). A thin dashed line in Fig.(b) is the one in case of “free quark decay”.

As is seen in Figs. 3(b) and 4(b), the confined effect is small in the non-relativistic region with large $Q^2$ ($\omega \sim 1$), and the predicted spectra are close to the ones in the case of free quark decay. In the relativistic region with small $Q^2$ ($\omega \sim \omega_{\text{max}}$) the confined effect becomes very large. It is interesting that we are led to good fits as a result of this large effects.

As is seen from Table II the values of $V_{cb}$ are mutually consistent for $B \rightarrow D^*$
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and $B \to D$ decays. This is required from the viewpoints of HQET and the boosted LS-coupling scheme.

The predicted spectrum for $B \to \rho l \bar{\nu}_l$ decay in unit of $V_{ub}$, $d\Gamma/dq^2 \equiv d\Gamma/(dq^2|V_{ub}|^2)$, is shown in Fig. 5, where the spectrum for “free quark decay” is also given. It is seen that the confined effects drastically change the spectrum of $B \to \rho$ decay.

In Fig. 6 the decay spectra for $B \to D^* l \bar{\nu}_l$ and $B \to \rho l \bar{\nu}_l$ predicted by COQM are shown and compared with the other models, WSB, KS, ISGW and ISGW2 models.

All models give similar results for $B \to D^* l \bar{\nu}_l$, while much different ones for $B \to \rho l \bar{\nu}_l$. The spectra for the latter predicted by COQM are similar to those of WSB, KS (ISGW) model in the relativistic (non-relativistic) region of $Q^2$, that is, $Q^2 \sim Q_{\text{max}}^2$ ($Q^2 \sim 0$). This fact seems to reflect the theoretical backgrounds of the respective models. In WSB and KS models, the absolute values of FF’s at $Q^2 = 0$ are fixed by the overlapping of wave functions of the scalar harmonic oscillator model in the infinite momentum frame. The ISGW model is essentially a non-relativistic (NR) model, and the FF’s are given by the overlapping of NR-meson wave functions, which are determined through the analysis of mass spectra of meson systems. Accordingly it may be reliable in the NR-region, $Q^2 \sim Q_{\text{max}}^2$. The spectra of ISGW2 model, which is updated from the original model, become closer in the relativistic region to those of COQM, which has a reliable kinematical framework in both relativistic and non-relativistic regions.
Presently there have been reported no experimental spectra for the $B \to \rho l \bar{v}_l$ decay. However, by comparing the theoretical values of $\tilde{\Gamma}(\equiv \Gamma/|V_{KM}|^2)$ with the experimental decay widths $\Gamma$’s for $B \to D/D^* l \bar{v}_l$ and $B \to \rho l \bar{v}_l$ processes, we can also determine the values of $V_{KM}$-elements. The relevant values of $V_{KM}$ thus obtained are collected and compared with the results obtained in the above models in Table III. There we have also given the results in the case of free quark decay. It is to be noted that $\tilde{\Gamma}$’s are much smaller, especially in $B \to \rho$ decay, than $\Gamma$’s. The $V_{c\bar{b}}$-values in Table III are consistent to those in Table II obtained from the decay spectra. They are nearly the same as the estimate by HQET, $0.038\pm0.007$. Our $V_{ub}$-value is also consistent to the conventional estimate, $(2 \sim 5) \times 10^{-3}$, derived by various other methods. From Table III we see that especially the $\tilde{\Gamma}$ for $B \to \rho l \bar{v}_l$ shows large model-dependence, and experimental studies on this process seem important to select the models.

Table III. Our values of $V_{cb}$ and $V_{ub}$ estimated from decay widths of $B \to D B \to D^*$ and $B \to \rho$ processes. The theoretical values without (with) brackets corresponds to case A(B). $\tilde{\Gamma}$’s obtained in the other models (WSB, KS, ISGW and ISGW2) are also given.

\[
\begin{array}{|c|c|c|}
\hline
 & B \to D l \bar{v}_l & B \to D^* l \bar{v}_l & B \to \rho l \bar{v}_l \\
\hline
\Gamma^{exp} & (11.3 \pm 2.0) \times 10^{-3} \text{ ps}^{-1} & (29.9 \pm 3.9) \times 10^{-3} \text{ ps}^{-1} & (16.0 \pm 5.6) \times 10^{-3} \text{ ps}^{-1} \\
V_{KM} & V_{cb}=0.0396\pm0.0036 & V_{cb}=0.0372\pm0.0025 & V_{ub}=(3.1 \pm 0.5) \times 10^{-3} \\
 & (0.0399\pm0.0036) & (0.0374\pm0.0025) & (3.2 \pm 0.6) \times 10^{-3} \\
\Gamma^{theor} & 18.7 \text{ ps}^{-1} & 41.9 \text{ ps}^{-1} & 150 \text{ ps}^{-1} \\
\hline
\Gamma^{theor} & 7.18(7.06) \text{ ps}^{-1} & 21.6(21.4) \text{ ps}^{-1} & 17.0(15.8) \text{ ps}^{-1} \\
(\text{WSB}) & 8.08 \text{ ps}^{-1} & 21.9 \text{ ps}^{-1} & 26.1 \text{ ps}^{-1} \\
\hline
\Gamma^{(\text{KS})} & 8.3 \text{ ps}^{-1} & 25.8 \text{ ps}^{-1} & 33.0 \text{ ps}^{-1} \\
\hline
\Gamma^{(\text{ISGW})} & 11 \text{ ps}^{-1} & 25 \text{ ps}^{-1} & 8.3 \text{ ps}^{-1} \\
\hline
\Gamma^{(\text{ISGW2})} & 11.9 \text{ ps}^{-1} & 24.8 \text{ ps}^{-1} & 14.2 \text{ ps}^{-1} \\
\hline
\end{array}
\]

§5. Concluding Remarks

We have studied, applying COQM, the spectra of semi-leptonic decay of B-meson, $B \to D^* l \bar{v}_l$ and $B \to D l \bar{v}_l$, which are known experimentally with high precisions, and obtained the consistent results to the experiments as a result of taking account of large quark confined effects. The values of $V_{cb}$ determined from these two decay spectra are mutually consistent. The $B \to D, D^*$ and $\rho \ l \bar{v}_l$ decay widths are also reproduced satisfactorily with the presently accepted values of the relevant $V_{KM}$-elements. These facts seem to give an evidence for validity of the framework of COQM, the boosted LS-coupling scheme, describing the meson systems.

The framework of COQM is also applicable directly to the transitions between hadrons including excited states, such as $B \to D^{**} l \bar{v}_l$, which will be treated elsewhere.

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