Spin-Independent Confining Force and a Boosted $LS$-Coupling Scheme for Covariant Description of Hadron World

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The essential kinematical framework and physical backgrounds of the covariant oscillator quark model are reviewed in the light of its recent progress, obtained through a universal treatment of hadron mass spectra and of weak transition form factors in the light-through-heavy quark meson and baryon systems.

Recently the heavy quark effective theory (HQET) has aroused wide interests among high energy physicists as a promising effective theory describing strong interactions of heavy quarks in the framework of QCD. Especially it is interesting that HQET, resorting to the heavy quark symmetry (HQS), is able to derive the relations among weak transition form factors (FF's) in the heavy-light-quark system and to evaluate the "genuine value" (without the binding effects of heavy hadrons) of relevant Kobayashi-Maskawa (KM) matrix element, $V_{cb}$, in the limit of infinite heavy quark mass $m_Q=\infty$.

It may be interesting and quite desirable if there is any means to estimate similarly the other elements of KM-matrix, although the straight extension of HQET seems to be almost impossible. Here we should like to mention that the same FF relations and a similar value of $V_{cb}$ are also obtained in the covariant oscillator quark model (COQM), where all meson and baryon systems with any flavor-configurations are unifiedly described in a covariant way. Actually we have recently applied it to various weak-transition processes of meson and baryon systems to estimate the general elements of KM-matrix. For these years it has also been applied to wide regions of hadron phenomena, leading to considerable successes. Considering the present stage of QCD, that there is no established effective method to estimate the binding effects of hadrons, we feel that it may be of some use to review the essential kinematical framework and physical backgrounds of COQM, in comparison with those of HQET. That is a purpose of the present work.

* The COQM has a long history of development since the bilocal theory by Yukawa 1950 and has been developed by many authors (mostly in Japan). As for its review and the references, see an article recently given by us.
hadrons.

Spin-independent confining force and global structure of hadron spectra

In investigating the hadron level structures, it is, in most of the potential models based upon QCD, assumed that the potential is given as a sum of the two terms

\[ U = U_{\text{cont}} + U_{\text{pertQCD}}, \]

where the first (second) term is a confining (perturbative-QCD) potential independent (and/or dependent) of the quark spin. It is generally believed that the global level structures are, in the general flavor-configuration systems, determined by the potential \( U_{\text{cont}} \), and the \( U_{\text{pertQCD}} \) induces some mixings among the mass eigenstates determined by \( U_{\text{cont}} \). This standpoint seems to be still supported mainly by phenomenological facts, and its direct justification from QCD may be, especially in the light-quark system, difficult. The origin of this standpoint may be traced back to the successes of non-relativistic quark model (NRQM) almost thirty years ago, which has a general framework to be called the LS-coupling scheme, or \( SU(2) \times O(3) \) (including the flavor symmetry \( SU(3)_F \) concerning the light quark system, the \( SU_F(6) \times O(3) \) scheme). Its essential physical framework on the level structure of hadrons seems to be succeeded as being valid until now also with the heavy-quark freedom as follows:

i) Concerning the light-quark systems, it is phenomenologically a well-known fact that the global level structures of hadrons are described by the linearly-rising orbital Regge trajectories (of squared masses versus orbital angular momentum \( L \) concerning the \( O(3) \) space), while the fine structures are depending upon the quark-spin freedom \( S \). For example, in the case of ground state levels (with \( L=0 \)), the masses \( m(S) \) of levels with different \( S \)'s are regarded, in the zero-th approximation, to be equal as

\[ M(1) = M(0), \quad M\left(\frac{1}{2}\right) = M\left(\frac{3}{2}\right). \]

ii) Concerning the heavy-quark systems, it is theoretically expected that a treatment based on NRQM should be more effective than in the light-quark system; and the many extensive analyses of heavy-quarkonium mass spectra have been worked out from the above standpoint. The standpoint of HQS on the heavy-light-quark systems may be included in it from a general point of view, although HQS is

<table>
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<th>( q\bar{q} )</th>
<th>( \Omega/\text{GeV}^2 )</th>
<th>( (M_f^2 - M_p^2)/\text{GeV}^2 )</th>
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<td>( s\bar{c} )</td>
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<td>( c\bar{c} )</td>
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<td>0.718</td>
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able to give the more on level spectra in the low-mass region around the ground states.

iii) Recently we have shown semi-phenomenologically a promising possibility that the global level structures of meson⁹ and baryon¹⁰ systems with general flavor-configurations, not only with light flavors but also with heavy flavors, are well described by the linear orbital Regge trajectories with respective slopes $\Omega^{-1}[(\Omega) = (\text{mass})^2)$. On the other hand it is well known¹¹ that the splittings between the ground state mesons due to spin-dependence $\Delta M_{\tilde{S}} = M^2(1) - M^2(0)$ have phenomenologically almost the same magnitude regardless of their flavor combinations. The values of $\Omega$ and $\Delta M_{\tilde{S}}$ which is considered to be representing, respectively, the characteristic "squared-mass scales" due to $U_{\text{conf}}$ and $U_{\text{pertQCD}}$ are collected in Table I, where, for comparison, the corresponding splittings, hyperfine splittings $\Delta M_{ss} = M(1) - M(0)$, are also given. From Table I we see that generally $\Omega \gg \Delta M_{\tilde{S}}$, except for the light-quark meson system, for which $\Omega \sim \Delta M_{\tilde{S}}$, supporting our standpoint. In the viewpoint of HQS, one gives a special attention on the smallness of $\Delta M_{ss}$ of heavy-light quark systems.

**Boosted LS coupling scheme—framework of COQM**

One of the most important motives for COQM is to describe covariantly the center of mass motion of hadrons, keeping the considerable successes of NRQM on the static properties of hadrons. It is indispensable for any models in order to get meaningful quantitative results by applying also to hadron reactions. A keystone in COQM for doing this is treating directly the squared masses of hadrons, in contrasting the mass itself in the conventional approaches, with the above mentioned standpoint. This makes our covariant treatment simple and easy and is supported by a phenomenological fact described in the last subsection, iii). The general framework of COQM may be called the boosted LS-coupling¹² scheme, and the wave functions, being generally tensors in $U(4)\otimes O(3,1)$-space, reduce, in the hadron rest frame, to those in $SU(2)_S \otimes O(3)_L$-space in NRQM. The spinor and space-time portions of wave functions satisfy separately the respective covariant equations, the Bargmann-Wigner (BW) Equations for the former and the covariant oscillator equation (in the limit of pure-confining force) for the latter. The origin of the above mentioned relations of the FF's is in the use of BW spinor functions in COQM.

Concretely, all non-exotic $q\bar{q}$-mesons and $qqq$-baryons are described unifiedly by multi-local fields; bi-local and tri-local ones, respectively as

$$\Phi_{A, A_1, A_2}(x_1, x_2, x_3),$$

where the $x_i$'s are Lorentz four-vectors representing the space-time coordinates of constituent quarks or anti-quarks, $A=(a, a) (B=(b, \beta))$ describing the flavor and covariant spinor functions of quarks (or anti-quarks). The multi-local meson and baryon fields are supposed to satisfy respective wave equations of the Klein-Gordon type and are expanded in terms of Fierz-components, that is, eigen-functions of $H^2$. These are written as

$$\Phi(X, r, \cdots) = \sum_{P_n} (e^{iP_n X} \Psi^{(+)}(r, \cdots, P_n) + e^{-iP_n X} \Psi^{(-)}(r, \cdots, P_n)), \tag{4}$$
\[ M^2(r, \cdots, \partial/\partial r, \cdots) \Psi_n^{(\pm)}(r, \cdots, P_n) = M_n^2 \Psi_n^{(\pm)}(r, \cdots, P_n), \]

where \( X_\mu (r, \cdots) \) is a center of mass (relative) coordinate, and \( M^2 \) is a squared-mass operator depending on relative coordinate variables, and the first (second) terms of Eq. (4) correspond to the positive (negative) frequency parts of the center of mass plane-wave motion with a definite total four-momentum \( P_n \) and a mass \( M_n = \sqrt{-P_n^2} \).

As was mentioned above the spin portions, \( U_n(W_n) \), of positive (negative) frequency internal wave functions \( \Psi_n^{(+)}(r, \cdots, P_n) \equiv U_n(P)f_n(r, \cdots; P_n) \) (\( \Psi_n^{(-)} \equiv W_nf_n \)), satisfy the respective BW equations.

**BW spinor functions and “free” constituent Dirac equation in “Parton-Like Motion”**

The positive-frequency parts \( U \) of BW spinor functions for meson and baryon systems satisfy, respectively, the BW equations as

**Mesons:**

\[
(iP \cdot r + M)_{\alpha\beta} U(v)_{\alpha\beta} = 0, \quad U(v)_{\alpha\beta}(-iP \cdot r + M)_{\alpha\beta} = 0.
\]

**Baryons:**

\[
(iP \cdot r + M)_{\alpha\beta} U(v)_{\alpha\beta} = 0, \quad (iP \cdot r + M)_{\alpha\beta} U(v)_{\alpha\beta} = 0,
\]

\[
(iP \cdot r + M)_{\alpha\beta} U(v)_{\alpha\beta} = 0.
\]

These BW spinor functions are reducible and decomposed into the irreducible components for mesons and baryons, respectively, as follows:

**Mesons:**

\[
U_{n,A}^B = \frac{1}{2\sqrt{2}} [(-\gamma_5 P_{\mu}^n + i\gamma \cdot V_{\mu}^n)(1 + iv \cdot \gamma)]_{\alpha\beta},
\]

**Baryons:**

\[
U_{n,ABC} = \frac{1}{2\sqrt{2}} [(-\gamma_5 (1 + iv \cdot \gamma) C^{-1})_{\alpha\beta} U_{n,abc}^{(A)} + \frac{1}{2\sqrt{2}} [i\gamma_\mu (1 + iv \cdot \gamma) C^{-1}]_{\alpha\beta} U_{n,abc}^{(5)} + \frac{1}{\sqrt{3}} \{i\gamma_\mu + v_\mu \gamma_5 U_{n,abc}^{(5)} \}],
\]

where all the components depend on the four-velocity of hadrons, \( v_\mu = P_\mu/M \) and \( C \) (= \( \gamma_1 \gamma_2 \) in our representation) is an anti-particle conjugation matrix satisfying \( \gamma_\mu^T = -C\gamma_\mu C^{-1} \). In Eq. (8) the \( P_{\mu}(v)'s \) and the \( V_{\mu}(v)'s \) represent spin-singlet ("pseudo-scalar") Fierz-components and spin-triplet ("vector") ones, respectively, and satisfy the Klein-Gordon equation (and the Lorentz condition \( P_{\mu}V_{\mu} = 0 \)) with a common mass-value \( M_n \) determined by Eq. (5). In the case of ground levels \( P_n \) and \( V_{n,\mu} \) correspond to our relevant pseudo-scalar mesons and vector mesons with a degenerate mass (see Eq. (2)). In Eq. (9) the first (second) term is anti-symmetric (symmetric) with regard to the first and second Dirac-spinor-indices; and \( u_n^{(A)} \), \( u_n^{(5)} \) and \( u_n^{(5)} \) denote the spin 1/2 "Dirac spinor", the spin 3/2 "Rarita-Schwinger spinor-vector" and the spin 1/2 "Dirac spinor" Fierz-components, respectively, and satisfy the respective equations with a common mass-value \( M_n \) determined by Eq. (5). In the case of ground levels \( u_n^{(A)} \) and \( u_n^{(5)} \), and \( u_n^{(5)} \) correspond to spin 1/2 baryons, and spin 3/2 baryons, respectively, with a degenerate mass (see Eq. (2)). Here it may be instructive to note that the BW spinor for mesons (baryons) is a direct product of positive
and negative energy Dirac spinors (of three positive energy Dirac spinors) concerning respective constituent quarks or anti-quarks. The Pauli conjugate BW spinors are defined as, respectively,

\[ \bar{U}_n(v')^{a} = -\gamma_{4} v' U_{n(b',\nu')}^{t(a',\nu')}, \]  
and are written in terms of the irreducible components as

\[ \bar{U}_n(v')^{a} = \left[ \begin{array}{c} -\frac{1}{2} \gamma_{5}(1 + iv' \cdot \gamma) P_{n}\bar{v}(v') \, s^a + i\gamma_{5} \bar{\n}(v') \, s^a \end{array} \right], \]

and (12)

A set of equations for the negative-frequency parts \( W \) of BW spinor functions, corresponding to Eq. (6) through Eq. (12), are obtained by the change of sign of \( v_{\mu} \) (\( v_{\mu} \rightarrow -v_{\mu} \)).

The weak transition FF relations for heavy-light-quark meson systems mentioned at the beginning are derived, both in COQM and (as is well-known) in HQET, by using the decompositions\(^{10}\) Eqs. (8) and (11). Similarly, the FF relations for heavy-light-quark baryon systems are derived, resorting\(^{10}\) to Eqs. (9) and (12).

Here we should like to point out an interesting new aspect of BW spinors as spin wave functions of a composite system. The BW equations for meson systems Eq. (6) and for baryon systems Eq. (7) are easily seen to be equivalent, respectively, to the following "free" constituent Dirac equations with a constraint on the respective constituent momenta \( p_{i} \) and "effective"-masses \( m_{i}^{*} \) as

\[ \begin{align*}
\text{Mesons:} & \quad (ip_{1} \cdot \gamma + m_{1}^{*}) U(p_{1}, p_{2}) = 0, \quad U(-ip_{2} \cdot \gamma + m_{2}^{*}) = 0, \\
& \quad p_{1,2} = \frac{m_{1,2}^{*}}{m_{1}^{*} + m_{2}^{*}} P, \quad M = m_{1}^{*} + m_{2}^{*}; \\
\text{Baryons:} & \quad (ip_{1} \cdot \gamma + m_{1}^{*}) U(p_{1}, p_{2}, p_{3}) = 0, \quad (ip_{2} \cdot \gamma + m_{2}^{*}) U(p_{1}, p_{2}, p_{3}) = 0, \\
& \quad (ip_{3} \cdot \gamma + m_{3}^{*}) U(p_{1}, p_{2}, p_{3}) = 0, \\
& \quad p_{1,2,3} = \frac{m_{1,2,3}^{*}}{m_{1}^{*} + m_{2}^{*} + m_{3}^{*}} P, \quad M = m_{1}^{*} + m_{2}^{*} + m_{3}^{*}.
\end{align*} \]

The constraints, Eqs. (13b) and (14b), are rewritten, respectively, as

\[ \begin{align*}
\text{(Mesons):} & \quad v_{i} = \frac{p_{i}}{m_{i}^{*}} = \frac{P}{m_{i}^{*} + m_{2}^{*}} = v_{\mu}, \\
\text{(Baryons):} & \quad v_{i} = \frac{p_{i}}{m_{i}^{*}} = \frac{P}{m_{i}^{*} + m_{2}^{*} + m_{3}^{*}} = v_{\pi},
\end{align*} \]
implying\textsuperscript{\textdagger} that each constituent is in "parton-like motion" (even in our relevant 'exclusive' processes), and moving all with the equal velocity $v_M$ ($v_B$), that of total meson (baryon). In other words, this means that all relative four-momenta between any pair of constituents are vanishing.

In this connection we give a comment on the way of deriving the relevant FF relations for the meson system in HQET: For that it is generally believed to be necessary not both of the Dirac equations (13a) but only the former one concerning the heavy quark (the first quark) with the "heavy quark condition" as

$$v_{1\mu} = \frac{p_{1\mu}}{m_1^*} = \frac{P_\mu}{M} = v_M.$$  \hfill (17)

However, noting the general definition of center of mass (relative) momentum $P(q)$ of the meson system as

$$p_{1\mu} = \kappa_1 P_\mu + q_\mu, \quad p_{2\mu} = \kappa_2 P_\mu - q_\mu, \quad (\kappa_1 + \kappa_2 = 1, \kappa_i > 0)$$  \hfill (18)

the condition Eq. (17) necessarily leads to

$$p_{1\mu} = \kappa_1 P_\mu, \quad m_1^* = \kappa_1 M \quad \text{and so} \quad q_\mu = 0.$$  \hfill (19)

Then, due to the latter of Eq. (18), the second (light) quark should be also on the mass shell

$$p_{2\mu} = \kappa_2 P_\mu, \quad p_{2\mu} = -\kappa_2^2 M^2 = -m_2^*,$$  \hfill (20)

and, in turn, this implies that the Dirac equation on the second quark (the latter of Eq. (13a)) is also valid.

Thus, it seems to us that both of Eqs. (13a) (with (13b)), which are equivalent to the BW equations (6), are implicitly assumed in deriving the FF relations in HQET.

\textbf{Covariant oscillator space-time functions as effective expansion bases}

The squared-mass operator (5) is given, in the case of meson system, by the potential (1) as

$$\mathbb{M}^2 = dH, \quad H = -\frac{1}{2\mu} \frac{\partial^2}{\partial x_\mu^2} + U(x),$$

$$d = 2(m_1 + m_2), \quad \mu = m_1m_2/(m_1 + m_2),$$  \hfill (21)

where the $m_i$'s are the "kinematical" masses of respective constituent quarks. In the case of pure-confining limit with $U = U_{\text{const}} = (1/2)Kx_\mu^2$ ($K$ being a universal spring constant through any flavor-configuration systems) it is, in terms of the oscillator variables, represented as

$$\mathbb{M}^2 = \frac{1}{2}(a_\mu^* a_\mu + a_\mu a_\mu^*)\Omega, \quad \Omega = d(K/\mu)^{1/2},$$

$$a_\mu(a_\mu^*) = \frac{1}{\sqrt{2}\beta}(\beta x_\mu - \frac{\partial}{\partial x_\mu}), \quad \beta \equiv (\mu K)^{1/2}. \quad \hfill (22)$$

\textsuperscript{\textdagger} This may remind one the exciton picture of quarks mentioned in the old paper,\textsuperscript{10} where the essential framework of COQM had first appeared with a slightly different kinematics.
In order to make the redundant relative-time freedom "frozen", the following condition\(^{16}\) is supposed:

\[ \langle P_{\mu}x_{\nu} \rangle = \langle P_{\mu}p_{\nu} \rangle = 0 \quad \text{or} \quad \langle v_{\mu}x_{\nu} \rangle = \langle u_{\mu}p_{\nu} \rangle = 0, \]  

(23)

where \( \langle A \rangle \) denotes to take an expectation value of \( A \) concerning the internal space-time wave functions, \( p_{\mu} \) being a conjugate momentum of \( x_{\mu} = (x_1 - x_2)_{\mu} \). Choosing the definite-metric type solutions, Eq. (23) is replaced by a physical-state condition\(^{17}\)

\[ P_{\mu}a_{\mu}^{\dagger}|\text{phys}\rangle = 0, \]  

(24)

and the \( \mathcal{M}_0^2 \) in Eq. (22) becomes

\[ \mathcal{M}_0^2 = a_{\mu}^{\dagger}(P)a_{\nu}(P)\Omega, \quad a_{\mu}(P) = \left( \delta_{\mu\nu} + \frac{P_{\mu}P_{\nu}}{M^2} \right)a_{\nu}, \text{ etc.} \]  

(25)

In the meson rest-frame with \( P = 0 \), this becomes, in the physical state sub-space, a three-dimensional oscillator \( \mathcal{M}_0^2 = a_{\mu}^{\dagger}a_{\mu}\Omega + M_0^2 (M_0 \text{ is a phenomenological parameter, introduced here, representing the mass of ground states}), \) as is required in a boosted-LS coupling scheme. Here we give the explicit form of the internal space-time wave function, for example, of the ground state.

\[ f_0(P, x) = \langle x|G(P)\rangle = \frac{\beta}{\pi} \exp \left\{ - \frac{K}{2}(x^2 + x_0^2) \right\} \rightarrow 0 \text{ for } |x|, |x_0| \rightarrow \infty. \]  

(26)

It may be notable that this function has a desirable asymptotic behavior on both of \( |x| \) and \( |x_0| \), and leads to phenomenologically desirable meson form factors.\(^{19}\) The internal wave functions for the \( n \)-th excited-levels are expressed covariantly as

\[ f_{\nu_1\cdots
u_n}(P, x) = \langle x|a_{\nu_1}^{\dagger}(P)\cdots a_{\nu_n}^{\dagger}(P)|G\rangle. \]  

(27)

Accordingly, now it may be clearly seen that the expansion of multi-local meson fields in terms of Fierz-components, Eq. (4), is done in a completely covariant way.

In the case of baryon system with the two relative-coordinates essentially the same procedure as above is made.

Here it may be worthwhile to note that the mass spectra of meson and baryon systems are, in the pure-confining limit, unifiedly described by the squared mass operator (Eq. (22) in the case of mesons), which includes only quark masses \( m_q \) and a universal spring constant \( K \) as parameters. We have shown, in the previous works, that this simple description seems to be supported phenomenologically, as was mentioned. This, in addition to the other results of its wide applications, seems also to suggest that, although its direct connection to QCD is not yet clear, our description of confined systems, using the oscillator functions should be very effective.

In this connection we should like to point out general character of the use of oscillator functions that, even if \( U_{\text{cont}} \) were given by the other one, they may be still useful as general expansion bases with appropriate boundary condition Eq. (26) for the internal wave functions.
Excited hadrons and effective mass of constituent Dirac equation

In COQM the BW equations are supposed to be valid for the covariant spin-functions of all, not only the ground-state but also the excited-state mesons and baryons.

Accordingly, Eqs. (6)-(20) are also valid for them. There the respective mass values are determined as eigenvalues of $\hat{M}^2$ (see Eq. (5)). In the case of pure-confining limit, the squared masses of the $N$-th excited state are given as

$$M_N^2 = M_C^2 + N\Omega; \quad (M_C = M_0)$$

(28)

and they are also represented by the effective constituent masses, in the constituent equations, of mesons and baryons, respectively, as (see Eqs. (13b) and (14b))

Mesons: $$M_N = m_{1,n}^* + m_{2,n}^*,$$  \hspace{1cm} (29a)

Baryons: $$M_N = m_{1,n}^* + m_{2,n}^* + m_{3,n}^*.$$  \hspace{1cm} (29b)

On the other hand, in our recent works we have shown semi-phenomenologically the relations

Mesons: $$M_C = m_1 + m_2,$$  \hspace{1cm} Baryons: $$M_C = m_1 + m_2 + m_3,$$  \hspace{1cm} (30)

that is, the masses of ground states are given as a respective sum of kinematical masses of constituent quarks. These equations (28)~(30) lead to the relation

$$m_{1,n}^* = \gamma_N m_1, \quad \gamma_N = M_N/M_C,$$  \hspace{1cm} (31)

meaning that the effective constituent quark masses are variant and the heavier in the higher-excited states.

Due to this prescription of "variant effective-mass" of constituent quarks, the COQM as a boosted-LS coupling scheme becomes applicable to covariant description of all hadrons, the excited states as well as the ground states, that is, "hadron world". In contrast with this, in HQET or in HQS, the heavy quark mass $m_Q$ is taken to be a constant, and their treatment in the heavy-light quark system becomes the less effective for treatment of the higher-excited states.

Systematics of hadrons in COQM

Summarizing the contents of the preceding sections, all non-exotic mesons and baryons are described by bi-local and tri-local fields, respectively (Eq. (3)). The respective hadrons correspond to the Fierz-components of these multi-local fields (Eq. (5)). Their covariant spin functions are given by the relevant BW equations (6) and (7), which are equivalent to a set of "free" constituent Dirac equations with variant effective masses (Eq. (31)), describing the parton-like constituent motion (Eqs. (13) through (16)). The internal space-time wave functions, in the pure-confining limit, are given by the covariant oscillator wave functions (Eqs. (26) and (27)), which may be useful also as a general expansion bases with appropriate boundary conditions (Eq. (26)). Our scheme is applicable to describing the excited as well as the ground state hadrons, that is, all the hadron world.
Spin-Independent Confining Force and a Boosted LS-Coupling Scheme

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