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Estimate of Hadronic and Radiative Decay of the Heavy-Light Mesons

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Takayuki Matsuki[*]
Tokyo Kasei University, 1-18-1 Kaga, Itabashi, Tokyo 173-8602, JAPAN
E-mail: `matsuki@tokyo-kasei.ac.jp`

Toshiyuki Morii
Graduate School of Science and Technology, Kobe University, Nada, Kobe 657-8501, JAPAN
E-mail: `morii@kobe-u.ac.jp`

Kohichi Seo
Gifu City Women's College, 7-1 Hitoichiba-Kitamachi, Gifu 501-0192, JAPAN
E-mail: `seo@gifu-cwc.ac.jp`

We propose a method how to calculate decay amplitudes of the heavy-light mesons associated with one photon or one chiral light hadron, using our semi-relativistic model, which succeeds in predicting and/or reproducing recently discovered all the heavy-light mesons, i.e., $D/D_s/B/B_s$ including the so-called D_{sJ}. We also obtain the relativistic expression for the decay amplitudes by Lorentz-boosting the the rest-frame wave functions.

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[*] Speaker.

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1. Introduction

The advent of the narrow meson states $D_{s0}^*(2317)$ and $D'_{s1}(2457)$, the so-called D_{sJ}, discovered by BaBar [1] and CLEO [2] in 2003, respectively, has given great impact on experimentalists as well as theorists, and after that open charm/bottom hadrons of the heavy-light systems have been discovered one after another. Ten years before this discovery, we proposed a formulation for the semi-relativistic potential model [5], based on which we have calculated mass spectra of higher states of the heavy-light mesons. Subsequently to the discovery of D_{sJ}, another set of broad heavy mesons, $D_0^*(2308)$ and $D'_1(2427)$, were discovered by the Belle collaboration [3]. These mesons are identified as $c\bar{q}$ $(q = u/d)$ excited $(\ell = 1)$ bound states and have the same quantum numbers, $j^P = 0^+$ and 1^+, as D_{sJ}, respectively. The decay widths of these excited D_{sJ} mesons are narrow, since the masses are below the DK/D^*K threshold, and hence the dominant decay modes violate the isospin invariance, whereas the excited D mesons, $D_0^*(2308)$ and $D'_1(2427)$, are broad because there is no such restriction as in D_{sJ} cases. More recent experiments reported by CDF and D0 [4] found narrow B and B_s states with $\ell = 1$, $B_1(5720)$, $B_2^*(5745)$, $B_{s2}^*(5839)$, and $B_{s1}(5829)$. These are narrow because they decay through the D-waves. All these heavy-light mesons are well predicted and/or reproduced by our recent numerical calculations [6].

In this article, using the formulation developed in [7] that is based on [5], we briefly describe a formulation how to calculate one chiral-meson and one photon decay processes of the heavy-light systems, e.g., $D'_{s0} \to D_{s0}\pi$, $D'_{s0} \to D_{s0}\gamma$, etc.

2. Formulation

2.1 Hadronic Decay

The decay processes of the heavy-light systems have been extensively studied by many people [8, 9, 10]. Most of them semi-relativistically treat hadrons and the overlap of heavy mesons is estimated using their meson wave functions in their own models. However, even with a trial wave function, it can be shown that a naive estimate of the overlap of wave functions vanishes if we use the expressions given in Ref. [10]. In Ref. [8], the general tensor structure of the transition amplitudes were extensively studied and some general statements are obtained. In Ref. [9], based on Ref. [8] both the mass spectra and transition amplitudes are calculated and seem to be successful to reproduce the experimental data except for the so-called D_{sJ}. These papers [8, 9] adopt the chiral quark model. On the other hand, Ref. [10] adopt the effective Lagrangian for the heavy-light hadrons. This paper seems to be successful in reproducing the experimental decay widths if we disregard the detailed structure of the hadrons.

To construct our formulation, we adopt the chiral quark model to obtain coupling between the heavy-light mesons and chiral multiplets. This is because we construct our wave function from a light anti-quark and a heavy quark as shown below and it is easy to incorporate the chiral quark model into our formulation to construct the transition amplitudes. In our formulation [5] to calculate the mass spectra, the heavy meson wave functions are automatically obtained when we solve the eigenvalue equation for the heavy meson spectrum. In the former paper [7], we have derived how to calculate the Isgur-Wise function using our wave functions for the heavy-light mesons obtained in [6]. Using the similar formulation to [7], we can derive the formula how to calculate the hadronic transition amplitudes as

$$\begin{aligned}\langle X_f \left| L_q \right| X_i \rangle &= \left\langle X_f \left| \int d^4x\, q_i^\dagger O q_j \Sigma_{ij} \right| X_i \right\rangle = \left\langle X_f \left| \int d^4x\, q_j^{c\dagger} \tilde{O} q_i^c\, \Sigma_{ij} \int d^3y Q^\dagger Q \right| X_i \right\rangle \\ &= (2\pi)^4 \delta^4(P_i - P_f - P_\pi) \int d^3x\, \mathrm{Tr}\left(\psi_{X\,f}^\dagger \tilde{O} e^{i\vec{q}\cdot\vec{x}} \psi_{X\,i} \right) ,\end{aligned} \tag{2.1}$$

where the heavy quark number operator, $\int d^3yQ^\dagger Q = 1$, is inserted, $X_{i,f}$ are initial and final heavy-light mesons, respectively, ψ_X is its wave function, and we have substituted non-relativistic expressions for wave functions into $\langle X_f \left| L_q \right| X_i \rangle$. q^c is a charge conjugate of q, $P_{i,f}$ are initial and final four momentum of the states $X_{i,f}$, respectively, P_π is a four momentum of a chiral particle, and $\vec{q}$ is its space component. In Eq. (2.1), we have assumed one big assumption that the chiral hadron is regarded as the Nambu-Goldstone particle so that it is expressed by a point particle, which means it can be approximated as a free particle proportional to $\exp(i\vec{q}\cdot\vec{z})$. Here definitions are given by

$$L_q = \int d^4x q_i^\dagger(x) O q_j(x) \Sigma_{ij}(x), \quad \langle 0 \left| q_\alpha^c(x) Q_\beta(y) \right| X, P_X \rangle = \psi_{X\,\alpha\beta}(0, \vec{x} - \vec{y})\, e^{-iP_X\cdot y} ,$$

where L_q is the chiral Lagrangian in which light quarks couple to one chiral meson and $O = i\gamma^0\gamma^5 \not\partial$. We assume that the coupling between a light quark and a chiral hadron is given by the following construction, [11]

$$\begin{aligned}&\mathscr{L}_q = \tfrac{g_A}{\sqrt{2} f_\pi} \bar{q} \gamma^5 i \not\partial \Sigma q, + O(\partial^2) \quad q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}, \\ &\Sigma = \sqrt{2} \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix} ,\end{aligned} \tag{2.2}$$

where g_A is a coupling constant, f_π is a decay constant, and higher orders in Σ are neglected in $\mathscr{L}_q$. Equation (2.1) is essentially the same as that obtained in [8] and [9].

To obtain a relativistic expression, we first insert the relativistic expressions for wave functions in the Breit moving frame into $\langle X_f \left| L_q \right| X_i \rangle$ and then Lorentz-boost them back to the rest frame so that we can use our rest-frame wave functions. These wave functions have been used to calculate mass spectrum, which has been done in [7] and the relativistic result is given by

$$\langle X_f \left| L_q \right| X_i \rangle \propto \gamma^{-1} \int d^3x\, e^{i\vec{q}\cdot\vec{x}} \mathrm{Tr}\left[\psi_{X\,f}^\dagger G^2 \tilde{O} \psi_{X\,i} \left(G^T\right)^2 \right] , \tag{2.3}$$

where G is a Lorentz-boost operator and $\gamma = 1/\sqrt{1 - v^2}$ is a Lorentz factor with velocity v of a heavy meson. Please refer to Ref. [7] in the details.

2.2 Radiative Decay

With regard to radiative decays, there have been only non-relativistic treatment known [9, 10] and hence it is worthwhile to construct a formulation for radiative decay processes as relativistic as possible. Photon can couple to both light quark and heavy quark electromagnetic currents, $j^\mu = e_q q^\dagger \gamma^0 \gamma^\mu q + e_Q Q^\dagger \gamma^0 \gamma^\mu Q$. By replacing L_q in Eq. (2.1) with $L_{QED} = \int d^4x\, j^\mu A_\mu$, we can derive a formula for the radiative decay. The expression is, however, somewhat intricate because we need to insert a different number operator for each electromagnetic current, i.e., $\int d^3y Q^\dagger Q$ for $q^\dagger \gamma^0 \gamma^\mu A_\mu q$ and $\int d^3y q^{c\dagger} q^c$ for $Q^\dagger \gamma^0 \gamma^\mu A_\mu Q$ to obtain appropriate wave functions. Hence we do not give this explicit expression here.

Including all these details, we are also doing numerical calculations, which will appear soon.[12]

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