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Decay constants of B mesons in the light cone quark model

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We study the pseudoscalar and vector B mesons decay constants within the framework of the light cone quark model (LCQM). LCQM deals with the wave function defined on the four-dimensional space-time plane defined by $x^+ = x^0 + x^3$ and includes the important relativistic effects that are neglected in the traditional constituent quark model. With the help of known values of constituent quark masses and the scale parameter β, we calculate the values of B mesons decay constants, respectively. The decay constants of pseudoscalar and vector mesons are useful for controlling the meson semileptonic decay widths, hadronic couplings and form factors.

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1. Introduction

The study of B-physics has been the focus of great interest for the past few decades, and many considerable amount of experimental as well as theoretical efforts have been done to understand the physics of B-mesons that will provide particularly sensitive probes to look into physics beyond the Standard Model (BSM) [1, 2]. Since B-mesons are the only mesons containing quarks of the third generation and thus their decays provide an unique opportunity to measure the most accurate values of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements which describe the couplings of the third generation of quarks to the lighter quarks. These matrix elements are the fundamental parameters of the Standard Model (SM) and their precise measurement will allow us to test the unitarity of the quark mixing matrix and CP violation in the SM [3]. It is essential to know the values of decay constants reliably in order to measure the CKM matrix elements because uncertainty in the knowledge of decay constants make it difficult to extract precisely the CKM matrix elements from experimental data.

The decays of B-mesons play an important role in determining the parameters of the SM and some hadronic parameters in quantum chromodynamics (QCD), such as CKM matrix elements [4] and the meson decay constants [5]. The decay constant of a meson is an useful parameter to study the weak decay processes such as quark mixing, CP violation, etc. The determination of this parameter is of prime interest in order to constrain the CKM mixing matrix elements in the weak mesonic decays. The decay constants of pseudoscalar and vector mesons are useful for understanding the realization of chiral symmetry in QCD and for controlling the meson semileptonic decay widths, hadronic couplings and form factors. The understanding of decay constants is invaluable because they are single numbers expressing the amplitude for a meson to annihilate to a single particle (for e.g. a W boson or a photon), encapsulating information which reveals the inside structure of the hadron [6].

The theoretical calculation of the decay constants of B-mesons require non-perturbative treatment since at short distances, the interactions are dominated by strong force. Here we focus on such method that is useful for solving non-perturbative problems of hadron physics using light cone quark model (LCQM). The LCQM has been widely used in the phenomenological study of meson physics. It provides an advantage of the equal light cone time ($x^+ = x^0 + x^3$) quantization and includes the important relativistic effects that are neglected in the traditional constituent quark model [7, 8, 9]. Moreover, vacum fluctuations are absent in light cone field theory and the state can be expanded in fock space in terms of frame independent n particle light cone wave functions (LCWFs) [10]. The LCWFs are independent of the hadron momentum and thus are explicitly Lorentz invariant [11].

2. Decay constants for B mesons in LCQM

In the LCQM, the bound state of B meson consisting of a quark q and an antiquark $\bar{q}$ with total

PoS(DIS2017)143

momentum P and spin S can be written as [12]

$$|B(P,S,S_z)\rangle = \int \frac{dp_q^+ d^2\mathbf{p}_{q_\perp}}{16\pi^3} \frac{dp_{\bar{q}}^+ d^2\mathbf{p}_{\bar{q}_\perp}}{16\pi^3} 16\pi^3 \delta^3(\tilde{P}-\tilde{p}_q-\tilde{p}_{\bar{q}}) \times \sum_{\lambda_q,\lambda_{\bar{q}}} \Psi^{SS_z}(\tilde{p}_q,\tilde{p}_{\bar{q}},\lambda_q,\lambda_{\bar{q}})\, |q(p_q,\lambda_q)\bar{q}(p_{\bar{q}},\lambda_{\bar{q}})\rangle, \tag{2.1}$$

where B represents a pseudoscalar or vector B-meson and $p_{q(\bar{q})}$ is the on-mass shell light-front momentum of the constituent quark. The four-momentum $\tilde{p}$ is defined as

$$\tilde{p} = (p^+,\, \mathbf{p}_\perp),\ \mathbf{p}_\perp = (p^1,\, p^2),\ p^- = \frac{m^2+\mathbf{p}_\perp^2}{p^+}. \tag{2.2}$$

The light-front momenta p_q and $p_{\bar{q}}$ in terms of light-cone variables are

$$p_q^+ = x_1 P^+,\ \ p_{\bar{q}}^+ = x_2 P^+, \quad \mathbf{p}_{q_\perp} = x_1\mathbf{P}_\perp + \mathbf{k}_\perp,\ \ \mathbf{p}_{\bar{q}_\perp} = x_2\mathbf{P}_\perp - \mathbf{k}_\perp, \tag{2.3}$$

where $x_{1(2)}$ is the light-cone momentum fraction satisfying $x_1+x_2=1$ and $\mathbf{k}_\perp$ is the relative transverse momentum of the constituent.
In the momentum-space, light cone wave function Ψ^{SS_z} in Eq. (2.1) can be expressed as a covariant form

$$\Psi^{SS_z}(\tilde{p}_q,\tilde{p}_{\bar{q}},\lambda_q,\lambda_{\bar{q}}) = \frac{\sqrt{p_q^+ p_{\bar{q}}^+}}{\sqrt{2}\,\sqrt{M_0^2-(m_q-m_{\bar{q}})^2}}\, \bar{u}(p_q,\lambda_q)\,\Gamma\, v(p_{\bar{q}},\lambda_{\bar{q}})\ \phi(x,\mathbf{k}_\perp), \tag{2.4}$$

where $\phi(x,\mathbf{k}_\perp)$ describes the momentum distribution of the constituents in the bound state, and

$$M_0^2 = \frac{m_q^2+\mathbf{k}_\perp^2}{x_1} + \frac{m_{\bar{q}}^2+\mathbf{k}_\perp^2}{x_2}. \tag{2.5}$$

Also

$$\Gamma = \gamma_5 \qquad \text{(for pseudoscalar, } S=0\text{), and} \quad \Gamma = -\,\hat{\not{\varepsilon}}(S_z) + \frac{\hat{\varepsilon}\cdot(p_q-p_{\bar{q}})}{M_0+m_q+m_{\bar{q}}} \qquad \text{(for vector, } S=1\text{)}, \tag{2.6}$$

with

$$\hat{\varepsilon}^\mu(\pm1) = \left[\frac{2}{P^+}\vec{\varepsilon}_\perp(\pm1)\cdot\vec{P}_\perp,\, 0,\, \vec{\varepsilon}_\perp(\pm1)\right], \quad \vec{\varepsilon}_\perp(\pm1) = \mp(1,\pm i)/\sqrt{2}, \quad \hat{\varepsilon}^\mu(0) = \frac{1}{M_0}\left(\frac{-M_0^2+P_\perp^2}{P^+}, P^+, P_\perp\right). \tag{2.7}$$

We can normalize the B-meson state as

$$\langle B(P',S',S_z')|B(P,S,S_z)\rangle = 2(2\pi)^3 P^+ \delta^3(\tilde{P}'-\tilde{P})\delta_{S'S}\delta_{S_z'S_z}\ , \tag{2.8}$$

so that

$$\int \frac{dx\,d^2\mathbf{k}_\perp}{2(2\pi)^3}\,|\phi(x,\mathbf{k}_\perp)|^2 = 1. \tag{2.9}$$

In the present work, we use the Gaussian-type wave function [13]

$$\phi(x,\mathbf{k}_\perp) = \frac{4\pi^{3/4}}{\beta^{3/2}}\sqrt{\frac{dk_z}{dx}}\exp(-\mathbf{k}^2/2\beta^2), \tag{2.10}$$

where β is the scale parameter, $\mathbf{k} = (\mathbf{k}_\perp, k_z)$ and k_z is defined as

$$\begin{aligned} k_z &= (x-\frac{1}{2})M_0 + \frac{m_q^2 - m_{\bar{q}}^2}{2M_0}, \text{ and} \\ \frac{dk_z}{dx} &= \frac{M_0}{4x(1-x)}\left[1-\left(\frac{m_q^2-m_{\bar{q}}^2}{M_0^2}\right)^2\right]. \end{aligned} \tag{2.11}$$

Decay constants are defined through matrix elements of pseudovector and vector currents between B-meson state and the vacum

$$\begin{aligned} \langle 0|A^\mu|P\rangle &= i f_P P^\mu, \\ \langle 0|V^\mu|V\rangle &= f_V M_V \varepsilon^\mu. \end{aligned} \tag{2.12}$$

where P is the meson momentum, M_V is the mass of the vector meson, and ε^μ is the polarization vector, respectively.
Using light-cone wave function, the decay constants of the pseudoscalar and vector meson are given by [5]

$$f_P = 2\sqrt{6}\int \frac{dx d^2\mathbf{k}_\perp}{2(2\pi)^3}\phi(x,\mathbf{k}_\perp)\frac{\mathscr{A}}{\sqrt{\mathscr{A}^2+\mathbf{k}_\perp^2}}, \tag{2.13}$$

$$\begin{aligned} f_V &= 2\sqrt{6}\int \frac{dx d^2\mathbf{k}_\perp}{2(2\pi)^3}\frac{\phi(x,\mathbf{k}_\perp)}{\sqrt{\mathscr{A}^2+\mathbf{k}_\perp^2}}\frac{1}{M_0}\Big\{m_q m_{\bar{q}} + x(1-x)M_0^2 + \\ &\quad \mathbf{k}_\perp^2 + \frac{\mathscr{B}}{2W}\left[\frac{m_q^2+\mathbf{k}_\perp^2}{1-x} - \frac{m_{\bar{q}}^2+\mathbf{k}_\perp^2}{x} - (1-2x)M_0^2\right]\Big\}, \end{aligned} \tag{2.14}$$

where

$$\begin{aligned} \mathscr{A} &= m_q x + m_{\bar{q}}(1-x), \\ \mathscr{B} &= m_q x - m_{\bar{q}}(1-x), \\ W &= M_0 + m_q + m_{\bar{q}}. \end{aligned}$$

For a given value of β, f_P and f_V can be calculated from Eqs. (2.13) and (2.14) using constituent

quark masses of d, s and b quarks, respectively.
We plot the decay constants f_P and f_V of B_d and B_s mesons as functions of parameter β in the LCQM using the constituent quark masses given by [5]

$$m_d = 0.25 \text{ GeV},\ m_s = 0.38 \text{ GeV},\ m_b = 4.8 \text{ GeV}. \tag{2.15}$$

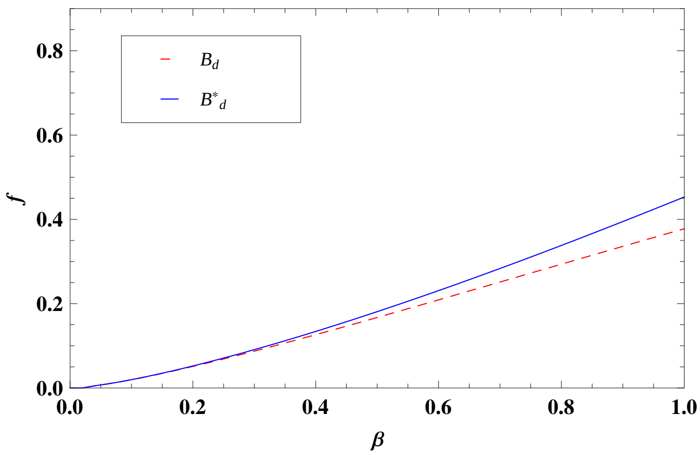

Figure 1: f_{B_d} and $f_{B_d^*}$ as functions of the parameter β (in GeV).

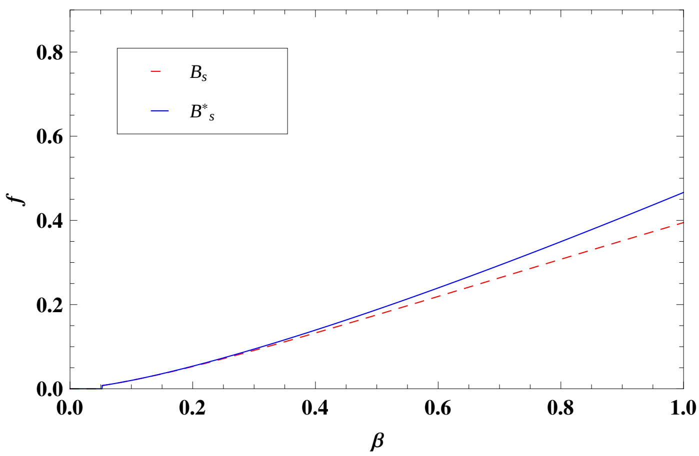

Figure 2: f_{B_s} and $f_{B_s^*}$ as functions of the parameter β (in GeV).

Figs. 1 and 2 show the dependence of the decay constants with respect to the parameter β which indicate that in order to get the reliable results for the decay constants, it is essential to obtain the precise value of β. Various potential models [14, 15, 16, 17] have been used in the literature to obtain the accurate values of the parameter β. In the present work, we use the β's ($\beta_{B_d} = 0.580$ GeV and $\beta_{B_s} = 0.636$ GeV) obtained by fitting harmonic-oscillator wave functions to the rms radii of the wave functions from the variational calculation of the relativistic Hamiltonian

by Capstick and Godfrey [14, 15].
Using the above values of β and the constituent quark masses of d, s and b quarks in Eq. (2.15), the results we obtained for decay constants of pseudoscalar and vector B-mesons in LCQM are as follows:

$$f_{B_d} = 201 \text{ MeV}, \quad f_{B_d^*} = 221 \text{ MeV},$$
$$f_{B_s} = 235 \text{ MeV}, \quad f_{B_s^*} = 259 \text{ MeV}.$$

Our predictions for the pseudoscalar decay constants are in good agreement with the available experimental data ($f_{B_d} = 190.9(4.1)$ MeV and $f_{B_s} = 227.2(3.4)$ MeV) [18].
In summary, we calculated the decay constants for pseudoscalar and vector B-mesons in the light cone formalism using the known values of constituent quark masses and the scale parameter β, respectively and then compared our results with the available experimental data. We found that our results are in good agreement with the experimental measurements.

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