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Study of twist-2 distribution amplitudes and the decay constants of pseudoscalar and vector heavy mesons in light-front quark model

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We study the twist-2 distribution amplitudes (DAs) and the decay constants of pseudoscalar as well as the longitudinally and transversely polarized vector heavy (D, D_s, B, B_s) mesons in the light-front quark model with the Coulomb plus exponential-type confining potential $V_{\rm exp} = a + be^{\alpha r}$ in addition to the hyperfine interaction. We first compute the mass spectra of ground state pseudoscalar and vector heavy mesons and fix the model parameters necessary for the analysis, applying the variational principle with the trial wave function up to the first three lowest order harmonic oscillator (HO) wave functions $\Phi(x, \mathbf{k}_\perp) = \sum_{n=1}^{3} c_n \phi_{nS}$. We then obtain the numerical results for the corresponding decay constants. We analyze the variation of DAs as a function of momentum fraction. We also compare our results with the available experimental data as well as with the other theoretical model predictions.

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1. Introduction

The nonperturbative structure of the hadron is well described by the hadronic or quark distribution amplitudes (DAs) which not only encode important information on bound states in QCD but also play an essential role in describing the various hard exclusive processes [1, 2] of QCD via the factorization theorem in analogous to parton distributions in inclusive processes. They also help in understanding the distribution of partons in terms of the longitudinal momentum fraction as they are the longitudinal projection of the hadronic wave functions obtained by integrating out the transverse momenta of the fundamental constituents of the hadron. Hadronic DAs are defined in terms of vacuum-to-hadron matrix elements of particular non-local quark or quark-gluon operators. The lowest moments of the hadronic DAs for a quark and an antiquark inside a meson provide us the knowledge of decay constants that are considered as direct source of information on the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, i.e. the fundamental parameters of the SM. The precise determination of decay constants will further allow us to test the unitarity of the quark mixing matrix and CP violation in the SM [3].

The present work is focused on the study of the ground state pseudoscalar and vector heavy (D, D^*, D_s, D_s^*, B, B^*, B_s, B_s^*) mesons mass spectra. The decay constants and the twist-2 DAs of pseudoscalar, longitudinally and transversely polarized vector heavy mesons have been studied in detail using the light-front quark model (LFQM) based on the idea of modelling the potential. This study will not only provide essential informations on the understanding of the universal nonperturbative quantities but also help further analyses of the hard exclusive processes.

2. Light-front quark model

Our LFQM is based on the idea that we consider the radial wave function $\Phi(x,\mathbf{k}_\perp)$ as a trial wave function for the variational principle to the QCD-motivated Hamiltonian [4, 5, 6]

$$H_{\text{c.m.}} = \sqrt{\mathbf{k}^2+m_q^2}+\sqrt{\mathbf{k}^2+m_{\bar{q}}^2}+V_{q\bar{q}}, \tag{2.1}$$

where $V_{q\bar{q}}$ is the effective interaction potential between quark and antiquark in the rest frame of the meson which is given by Coulomb (V_{Coul}) plus exponential-type potential (V_{exp}) in addition to the hyperfine interaction (V_{hyp}). That is,

$$\begin{aligned} V_{q\bar{q}} &= V_{\text{exp}}+V_{\text{Coul}}+V_{\text{hyp}} \\ &= a+be^{\alpha r}-\frac{4\kappa}{3r}+\frac{2}{3}\frac{\mathbf{S_q}\cdot\mathbf{S_{\bar{q}}}}{m_q m_{\bar{q}}}\nabla^2 V_{\text{Coul}}, \end{aligned} \tag{2.2}$$

where a, b and α are the parameters of the potential, κ is the strong coupling constant which has been taken as one of the variation parameter in this work, $\langle \mathbf{S_q}\cdot\mathbf{S_{\bar{q}}}\rangle = -3/4\,(1/4)$ for the pseudoscalar (vector) meson, respectively. We use the radial wave function $\Phi(x,\mathbf{k}_\perp)$ as an expansion of the true wave function in the three lowest order HO wave functions $\Phi(x,\mathbf{k}_\perp)=\sum_{n=1}^{3} c_n\phi_{nS}$ for both pseudoscalar and vector mesons [7]. The optimized values of the constituent quark masses and other potential parameters that give the best fit of the ground state mass spectra of mesons are summarized in Table 1.

Table 1: Constituent quark masses and the potential parameters σ, α, and a (in units of GeV) obtained by the variational principle for the Hamiltonian with a smeared-out hyperfine interaction. Here $q = u$ and d.

m_q	m_s	m_c	m_b	σ	α	a
0.202	0.405	1.725	5.182	0.451	0.15	−1.075

Due to the presence of hyperfine interaction in our variational process, we have different sets of β values for pseudoscalar and vector mesons, respectively. The optimal Gaussian parameters $\beta^P_{q\bar{q}}$ and $\beta^V_{q\bar{q}}$ for pseudoscalar and vector mesons obtained by the variational principle are listed in Table 2. Using these fixed model parameters, we obtained the ground state pseudoscalar $(D_{(s)}, B_{(s)})$ and vector $(D^*_{(s)}, B^*_{(s)})$ meson mass spectra. Our results are summarized in Table 3, comparing with the experimental data [8] and the previous results obtained from the linear and HO potentials [9, 10].

Table 2: The Gaussian parameter β (GeV) for ground state pseudoscalar (D, D_s, B, B_s) and vector (D^*, D^*_s, B^*, B^*_s) mesons obtained by the variational principle. Here $q = u$ and d.

J^{PC}	β_{qc}	β_{cs}	β_{qb}	β_{bs}
0^{-+}	0.2980	0.3010	0.3191	0.3290
1^{--}	0.2818	0.2926	0.3115	0.3250

Table 3: Ground state mass spectra (in units of GeV) of pseudoscalar $(D_{(s)}, B_{(s)})$ and vector $(D^*_{(s)}, B^*_{(s)})$ mesons obtained from the exponential type potential and their comparison with the experimental data [8] and the LFQM results obtained from the linear and HO potentials [9, 10].

	M_D	M_{D^*}	M_{D_s}	$M_{D^*_s}$	M_B	M_{B^*}	M_{B_s}	$M_{B^*_s}$
Present work	1.803	1.884	1.929	1.971	5.212	5.242	5.313	5.329
Exp. [8]	1.869	2.010	1.968	2.112	5.279	5.325	5.367	5.415
LFQM, Lin [9]	1.836	1.998	2.011	2.109	5.235	5.315	5.375	5.424
LFQM, HO [9]	1.821	2.024	2.005	2.150	5.235	5.349	5.378	5.471
LFQM [10]	1.875	1.962	1.981	2.031	5.233	5.268	5.314	5.333

3. Numerical Results

3.1 Decay Constants

For the present calculations of the decay constants, we include the systematic errors in our analysis obtained both from the $\pm 10\%$ variation of β values for the fixed quark masses and the $\pm 10\%$ variation of quark masses for the fixed β values. In Tables 4 and 5, we present our predictions for the decay constants of pseudoscalar, longitudinally, and transversely polarized vector D and B mesons, respectively.

PoS(LC2019)038

Table 4: Pseudoscalar, longitudinally and transversely polarized vector D meson decay constants (in units of MeV) in the present work and their comparison with the available experimental data and other theoretical model predictions.

	f_D	f_{D^*}	$f^{\perp}_{D^*}$	f_{D_s}	$f_{D_s^*}$	$f^{\perp}_{D_s^*}$
Present work	$197^{+19+0.2}_{-20-1.0}$	230^{+29-5}_{-28+6}	208^{+24-3}_{-24+3}	$219^{+21-0.2}_{-22-0.8}$	253^{+31-6}_{-31+6}	233^{+26-3}_{-26+3}
Exp. [8]	203.7 ± 4.7	–	–	257.8 ± 4.1	–	–
LFQM, Lin [9]	197	239	–	233	274	–
LFQM, HO [9]	180	212	–	218	252	–
LFQM, Lin [10]	208	230	–	231	260	–

Table 5: Pseudoscalar, longitudinally and transversely polarized vector B meson decay constants (in units of MeV) in the present work and their comparison with the available experimental data and other theoretical model predictions.

	f_B	f_{B^*}	$f^{\perp}_{B^*}$	f_{B_s}	$f_{B_s^*}$	$f^{\perp}_{B_s^*}$
Present work	163^{+21-4}_{-20+4}	172^{+24-6}_{-23+6}	165^{+22-5}_{-21+5}	184^{+23-4}_{-23+4}	194^{+26-6}_{-25+7}	187^{+24-5}_{-24+6}
Exp. [8]	188 ± 25	–	–	–	–	–
LFQM, Lin [9]	171	186	–	205	220	–
LFQM, HO [9]	161	173	–	208	223	–
LFQM, Lin [10]	181	188	–	205	216	–

3.2 Quark Distribution Amplitudes

The quark DAs are defined in terms of the matrix elements of non-local operators that are sandwitched between the vacuum and the meson states [11]. The explicit forms of quark DAs in our LFQM are given by [12]

$$\phi_P(x) = \frac{2\sqrt{6}}{f_P} \int \frac{d^2\mathbf{k}_\perp}{\sqrt{16\pi^3}} \sqrt{\frac{\partial k_z}{\partial x}} \Phi(x,\mathbf{k}_\perp) \frac{\mathscr{A}}{\sqrt{\mathscr{A}^2 + \mathbf{k}_\perp^2}}, \tag{3.1}$$

$$\phi_{V\parallel}(x) = \frac{2\sqrt{6}}{f_V} \int \frac{d^2\mathbf{k}_\perp}{\sqrt{16\pi^3}} \sqrt{\frac{\partial k_z}{\partial x}} \frac{\Phi(x,\mathbf{k}_\perp)}{\sqrt{\mathscr{A}^2 + \mathbf{k}_\perp^2}} \left\{ \mathscr{A} + \frac{2\mathbf{k}_\perp^2}{M_0 + m_q + m_{\bar{q}}} \right\}, \tag{3.2}$$

$$\phi_{V\perp}(x) = \frac{2\sqrt{6}}{f_V^\perp} \int \frac{d^2\mathbf{k}_\perp}{\sqrt{16\pi^3}} \sqrt{\frac{\partial k_z}{\partial x}} \frac{\Phi(x,\mathbf{k}_\perp)}{\sqrt{\mathscr{A}^2 + \mathbf{k}_\perp^2}} \left\{ \mathscr{A} + \frac{\mathbf{k}_\perp^2}{M_0 + m_q + m_{\bar{q}}} \right\}, \tag{3.3}$$

Our results for the quark DAs of D, D^*, D_s and D_s^* mesons show much broader shapes than those of B, B^*, B_s and B_s^* mesons due to the large mass difference between b and c quarks.

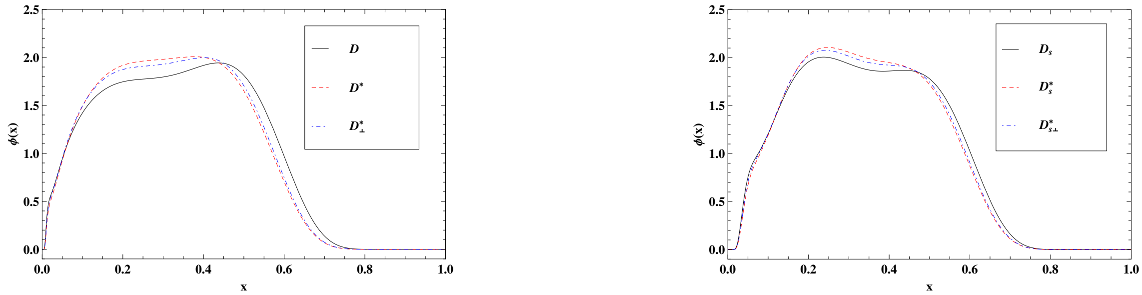

Figure 1: Normalized DAs for the heavy pseudoscalar (solid line), longitudinally (dashed line) and transversely (dotted dashed line) polarized vector D (left panel) and D_s (right panel) mesons.

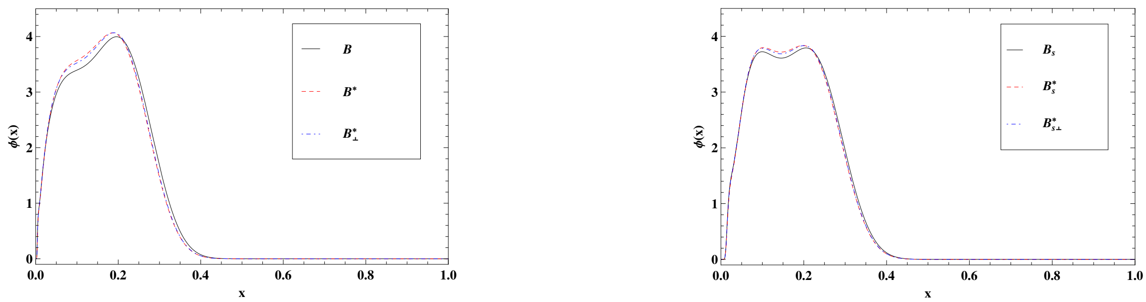

Figure 2: Normalized DAs for the heavy pseudoscalar (solid line), longitudinally (dashed line) and transversely (dotted dashed line) polarized vector B (left panel) and B_s (right panel) mesons.

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