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Properties of Orbitally Excited Heavy-Light Mesons

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Abstract

Orbitally excited heavy-light mesons are potentially important as tools for tagging the flavors and momenta of ground-state pseudoscalars detected through weak decays. We use heavy-quark symmetry supplemented by insights gleaned from potential models to estimate masses and widths of p-wave B, B_s, and D_s mesons. We generalize these results to higher excitations.

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Incisive study of particle-antiparticle mixing and CP-violation for neutral B mesons requires that the quantum numbers of the meson be identified at the time of production. That identification can be made by observing the decay of a B or $\bar{B}$ produced in association with a particle of opposite b-number whose decay signals the flavor of the neutral B of interest. The efficiency of flavor identification might be considerably enhanced if the neutral B under study were self-tagging [1].

Charmed mesons have been observed as (strong) decay products of orbitally excited $(c\bar{q})$ states, through the decays $D^{**} \to \pi D$ and $D^{**} \to \pi D^{*}$ [2]. The charge of the pion emitted in the strong decay signals the flavor content of the charmed meson. If significant numbers of B mesons are produced through one or more narrow excited $(\bar{b}q)$ states, the strong decay $B^{**\pm} \to B^{(*)0}\pi^{\pm}$ tags the neutral meson as $(\bar{b}d)$ or $(b\bar{d})$, respectively.

The primary application of B^{**}-tagging would be in the search for the expected large CP-violating asymmetry in $(B^0$ or $\bar{B}^0) \to J/\psi K_S$ decay [3]. B^{**}-tagging may also resolve kinematical ambiguities in semileptonic decays of charged and neutral B mesons by choosing between two solutions for the momentum of the undetected neutrino. In hadron colliders and Z^0-factories, kinematic tagging may make practical a high-statistics determination of the form factors in semileptonic weak decay, and might ultimately allow precise measurements of V_{cb} and V_{ub} [4,5]. The study of B_s-$\bar{B}_s$ mixing would be made easier if the kaon charge in the decay $B^{***} \to K^{\pm}(B_s$ or $\bar{B}_s)$ served as a flavor tag. Overall, efficient B^{**}-tagging would dramatically enhance the prospects for studying CP-violation and B_s-$\bar{B}_s$ mixing.

In this Letter, we estimate the masses, widths, and branching fractions of orbitally excited B, D_s, and B_s states from the properties of corresponding K and D levels. Our results show that one requirement for the utility of B^{**}-tagging, narrow resonances, is likely to be met by the B_2^* and B_1. Experiment must rule on the strength of these lines and the ratio of signal to background.

For hadrons containing a heavy quark Q, quantum chromodynamics displays additional symmetries in the limit as the heavy-quark mass m_Q becomes large compared with a typical QCD scale [6]. These heavy-quark symmetries are powerful aids to understanding the spectrum and decays of heavy-light $(Q\bar{q})$ mesons. Because $m_b \gg \Lambda_{\text{QCD}}$, heavy-quark symmetry should provide an excellent description of the B and B_s mesons. It is plausible that properties of D mesons, and even K mesons, should also reflect approximate heavy-quark symmetry.

One essential idea of the heavy-quark limit is that the spin $\vec{s}_Q$ of the heavy quark and the total (spin + orbital) angular momentum $\vec{j}_q = \vec{s}_q + \vec{L}$ of the light degrees of freedom are separately conserved [7]. Accordingly, each energy level in the excitation spectrum of $(Q\bar{q})$ mesons is composed of a degenerate pair of states characterized by j_q and the total spin $\vec{J} = \vec{j}_q + \vec{s}_Q$, i.e., by $J = j_q \pm \frac{1}{2}$. The ground-state pseudoscalar and vector mesons, which are degenerate in the heavy-quark limit, correspond to $j_q = \frac{1}{2}$, with $J = 0$ and 1. Orbital excitations lead to two distinct doublets associated with $j_q = L \pm \frac{1}{2}$.

Masses. The leading corrections to the spectrum prescribed by heavy-quark symmetry are inversely proportional to the heavy-quark mass. We may write the mass of a heavy-light meson as

$$M(n\mathrm{L}_J(j_q)) = M(1\mathrm{S}) + E(n\mathrm{L}(j_q)) + \frac{C(n\mathrm{L}_J(j_q))}{m_Q}\ , \tag{1}$$

where n is the principal quantum number and $M(1S) = [3M(1S_1) + M(1S_0)]/4$ is the mass of the ground state. The excitation energy $E(nL(j_q))$ has a weak dependence on the heavy-quark mass.

Let us focus first upon the $j_q = \frac{3}{2}$ states observed as narrow $D\pi$ or $D^*\pi$ resonances. We will show below that their counterparts in other heavy-light systems should also be narrow. Our overall strategy is to use the observed properties of the K and D mesons to predict the properties of the orbitally excited B, D_s, and B_s mesons. Experimental knowledge of the reference systems is still fragmentary, so we must appeal to potential models to estimate how the excitation spectrum varies with heavy-quark mass. Although nonrelativistic potential models have obvious limitations for systems that include light quarks, we find that the Buchmüller-Tye potential [8] gives a good account of the observed K, D, and D_s levels. The potential-model spectra can also serve as templates for unobserved states, particularly those along the leading Regge trajectory.

According to Eq. (1), the masses of the strange and charmed mesons with $j_q = \frac{3}{2}$ are given by

$$\begin{aligned}
M(2P_2)_K - M(1S)_K &= E(2P)_K + \frac{C(2P_2)}{m_s} \quad , \\
M(2P_1)_K - M(1S)_K &= E(2P)_K + \frac{C(2P_1)}{m_s} \quad , \\
M(2P_2)_D - M(1S)_D &= E(2P)_D + \frac{C(2P_2)}{m_c} \quad , \\
M(2P_1)_D - M(1S)_D &= E(2P)_D + \frac{C(2P_1)}{m_c} \quad ,
\end{aligned} \tag{2}$$

where we have suppressed the j_q label for brevity. Upon identifying $E(2P)_D = E(2P)_K - \delta$, where $\delta = 32$ MeV is determined from the potential-model spectra, we are left with four linear equations in the five unknowns $E(2P)_K$, $C(2P_2)$, $C(2P_1)$, m_s^{-1}, and m_c^{-1}.

The K- and D-meson masses we use as experimental inputs are displayed in Table I. There is no ambiguity about the $2^+(\frac{3}{2})$ levels. We identify $D_1(2424)$ as a $j_q = \frac{3}{2}$ level because it is narrow, as predicted [11,12] by heavy-quark symmetry. We follow Ito et al. [13] in identifying $K_1(1270)$ as the $1^+(\frac{3}{2})$ level, because that assignment gives a consistent picture of masses and widths.

To proceed, we choose a value for the charmed-quark mass, m_c. After solving Eqs. (2), we verify the reasonableness of m_s and predict the $j_q = \frac{3}{2}$ masses for the B, D_s, and B_s families. We consider two sets of parameters inspired by J/ψ and Υ spectroscopy: $m_c = 1.48$ GeV, $m_b = 4.8$ GeV [8]; and $m_c = 1.84$ GeV, $m_b = 5.18$ GeV [14]. Both solutions [$C(2P_2) = (0.0495, 0.06155)$ GeV^2, $C(2P_1) = (-0.0029, -0.00358)$ GeV^2, $E(2P)_K = (0.4844, 0.48445)$ GeV, $m_s = (0.33, 0.41)$ GeV] yield reasonable values for the strange-quark mass. Their implications for the B, D_s, and B_s levels are consistent within 2 MeV. The average values are presented in Table I. Including the variation of excitation energy represented by the parameter δ has lowered the masses by 7, 26, and 32 MeV for the B, D_s, and B_s states.

Our prediction for the 1^+ D_s meson lies 34 MeV below the level observed [9] at 2536.5 ± 0.8 MeV. The spin-parity assignment for this state as 1^+, rather than 2^+, is suggested by the nonobservation of a KD decay mode and supported by a recent analysis of the helicity-angle distribution of the D^{*0} in the decay $D_{s1} \to D^{*0}K$ [15]. We take the discrepancy between calculated and observed masses as a measure of the limitations of our method.

The $2\mathrm{P}(\frac{1}{2})$ D mesons have not yet been observed, so we cannot predict the masses of other heavy-light states by this technique. Splitting within the multiplet can be estimated using Eq. (1) from the kaon spectrum alone. The small splitting between $K_0^*(1429)$ and $K_1(1402)$ implies that the $1^+(\frac{1}{2})$ and $0^+(\frac{1}{2})$ levels should be nearly degenerate in all the heavy-light systems. Chiral symmetry and heavy-quark symmetry combined suggest that, like their counterparts in the strange-meson spectrum, the heavy-light $j_q = \frac{1}{2}$ p-wave states should have large widths for pionic decay to the ground states [16]. This will make the discovery and study of these states challenging, and will limit their utility for B^{**}-tagging.

Decay widths. Consider the decay of an excited heavy-light meson H, characterized by $\mathrm{L}_J(j_q)$, to a heavy-light meson $H'(\mathrm{L}'_{J'}(j'_q))$, and a light hadron h with spin s_h. The amplitude for the emission of h with orbital angular momentum ℓ relative to H' satisfies certain symmetry relations because the decay dynamics become independent of the heavy-quark spin in the $m_Q \to \infty$ limit of QCD [11]. The decay amplitude can be factored [12] into a reduced amplitude $\mathcal{A}_\mathrm{R}$ times a normalized 6-j symbol,

$$\mathcal{A}(H \to H'h) = (-1)^{s_Q + j_h + J' + j_q}\, \mathcal{C}^{s_Q, j'_q, J'}_{j_h, J, j_q} \mathcal{A}_\mathrm{R}(j_h, \ell, j_q, j'_q),$$

where $\mathcal{C}^{s_Q, j'_q, J'}_{j_h, J, j_q} = \sqrt{(2J'+1)(2j_q+1)} \begin{Bmatrix} s_Q & j'_q & J' \\ j_h & J & j_q \end{Bmatrix}$ and $\vec{j}_h \equiv \vec{s}_h + \vec{\ell}$. The coefficients $\mathcal{C}$ depend only upon the total angular momentum j_h of the light hadron, and not separately on its spin s_h and the orbital angular momentum wave ℓ of the decay. The two-body decay rate may be written as

$$\Gamma^{H \to H'h}_{j_h, \ell} = (\mathcal{C}^{s_Q, j'_q, J'}_{j_h, J, j_q})^2 p^{2\ell+1} F^{j_q, j'_q}_{j_h, \ell}(p^2), \tag{3}$$

where p is the three-momentum of the decay products in the rest frame of H. Heavy-quark symmetry does not predict the reduced amplitude $\mathcal{A}_\mathrm{R}$ or the related $F^{j_q, j'_q}_{j_h, \ell}(p^2)$ for a particular decay. Once determined from the charmed or strange mesons, these dynamical quantities may be used to predict related decays, including those of orbitally excited B mesons. For each independent decay process, we assume a Gaussian form

$$F^{j_q, j'_q}_{j_h, \ell}(p^2) = F^{j_q, j'_q}_{j_h, \ell}(0) \exp(-p^2/\kappa^2), \tag{4}$$

and determine the overall strength of the decay and the momentum scale of the form factor by fitting to existing data. Our ability to predict decay rates depends on the quality of the information used to set these parameters.

In writing (3) we have ignored $1/m_Q$ corrections to heavy-quark symmetry predictions for decay rates, except as they modify the momentum p of the decay products. We assume that the momentum scale κ of the form factor in (4) is typical of hadronic processes (≈ 1 GeV) and that it varies little with decay angular momentum ℓ.

The decays $2\mathrm{P}(\frac{3}{2}) \to 1\mathrm{S}(\frac{1}{2}) + \pi$ are governed by a single $\ell = 2$ amplitude. To evaluate the transition strength $F^{\frac{3}{2}, \frac{1}{2}}_{2,2}(0)$, we fix $\Gamma(D_2^* \to D\pi) + \Gamma(D_2^* \to D^*\pi) = 25$ MeV, as suggested by recent experiments [2]. This determines all the pionic transitions between the 2P($\frac{3}{2}$) and 1S($\frac{1}{2}$) multiplets. The results are shown in Table II, where we indicate the variation of the predicted rates as the momentum scale κ ranges from 0.8 to 1.2 GeV. The strengths of K and η transitions are determined by $SU(3)$ [17]. The predictions agree well with what is known about the $L = 1$ D and D_s states. The ratio $\Gamma(D_2^* \to D\pi)/\Gamma(D_2^* \to D^*\pi) = 1.8$ is consistent with the Particle Data Group average, 2.4 ± 0.7 [9], and with a recent CLEO measurement, $2.1 \pm 0.6 \pm 0.6$ [18].

Increasing the D_{s1} and D_{s2}^* masses by 34 MeV to match the observations of D_{s1} increases each of the partial widths for those states by 1 or 2 MeV. The narrow width observed for D_{s1} is close to the prediction from heavy-quark symmetry. This suggests that mixing of the narrow 2P($\frac{3}{2}$) level with the broader 2P($\frac{1}{2}$) state [11,12] is negligible. This pattern should hold for B and B_s as well. We have also applied heavy-quark dynamics to the decays of the 2P($\frac{3}{2}$) strange mesons. The pionic transition rates given in Table II are in surprisingly good agreement with experiment.

Decays of the 2P($\frac{3}{2}$) states into a vector meson plus a 1S($\frac{1}{2}$) level are governed by three independent decay amplitudes characterized by $(j_h, \ell) = (2,2)$, $(1,2)$, and $(1,0)$. $SU(6)$ symmetry identifies the $(2,2)$ transition strength with the $F_{2,2}^{\frac{3}{2},\frac{1}{2}}(0)$ for pion emission. The two new amplitudes occur in a fixed combination that should be dominated by the $\ell = 0$ amplitude. We have to evaluate one new transition strength, $F_{1,0}^{\frac{3}{2},\frac{1}{2}}(0)$. Lacking measurements of partial widths for vector meson emission in the charmed states, and encouraged by the satisfactory pattern of pionic decay widths for the strange resonances, we use the decay rate $\Gamma(K_1(1270) \to \rho + K) = 37.8$ MeV to fix $F_{1,0}^{\frac{3}{2},\frac{1}{2}}(0)$. We smear the expression (3) for the partial width over a Breit-Wigner form to take account of the 150-MeV width of the ρ resonance.

The resulting estimates for the ρ transitions are also shown in Table II. The dependence on κ is much more pronounced than for the pseudoscalar transitions because of the wide variation in momentum over the ρ peak. Rates for $K^{**} \to K\omega$ decays follow from $SU(3)$ symmetry.

The results collected in Table II show that both the B_2^* and the B_1 states should be narrow (20 to 40 MeV), with large branching fractions to a ground-state B or B^* plus a pion. These states should also have significant two-pion transitions that we have modeled by the low-mass tail of the ρ resonance. The strange states, B_{s2}^* and B_{s1}, are very narrow ($\Gamma \lesssim 10$ MeV); their dominant decays are by kaon emission to the ground-state B and B^*. The consistent picture of K_1 and K_2^* decay rates supports the identification [13] of $K_1(1270)$ as the 2P$_1$($\frac{3}{2}$) level.

To assess the prospects for tagging B_s, we consider briefly the d-wave heavy-light mesons with $j_q = \frac{5}{2}$. Only the K mesons have been observed. The identification of the $K_3^*(1770)$ as a 3D$_3$($\frac{5}{2}$) level is clear. Two $J^P = 2^-$ levels, $K_2(1773)$ and $K_2(1816)$, are candidates for its partner [19]. Whatever the assignment for the 3D$_2$($\frac{5}{2}$) level, the splitting within the $j_q = \frac{5}{2}$ doublet will be very small for the D, B, D_s, and B_s systems. We use the Buchmüller-Tye potential [8] to estimate the masses of the $L = 2$ heavy-light states shown in Table III.

To evaluate the transition strength $F_{3,3}^{\frac{5}{2},\frac{1}{2}}(0)$ for pseudoscalar emission, we fix $\Gamma(K_3^* \to K^*\pi) = 45$ MeV. As before, $SU(6)$ symmetry determines the strength $F_{3,3}^{\frac{5}{2},\frac{1}{2}}(0)$ for vector meson emission. In the absence of measurements that would allow us to fix the other important decay amplitude, we have set $F_{2,1}^{\frac{5}{2},\frac{1}{2}}(0) = 0$. Our projections for vector-meson emission will therefore be underestimates. We summarize our expectations for the total widths of the 3D($\frac{5}{2}$) states in Table III.

The 3D($\frac{5}{2}$) B mesons will be broad (250 to 400 MeV), but decay with about thirty percent probability to B_s and B_s^* by emission of a K or K^*. The estimate for the branching fraction is less sensitive than the widths to variations in κ. The favorable branching fraction means that it might be possible to use B_3^* and B_2 decays to tag the B_s, in spite of the very large total widths.

Properties of orbitally excited heavy-light mesons will test the validity of heavy-quark symmetry, which may offer new insight into the spectrum of strange mesons. If the narrow B_2^* and B_1 are copiously produced with little background, efficient tagging of flavor and momentum may be at hand. Prospects for incisive B studies at high energies would then be dramatically enhanced [5].

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TABLES

TABLE I. Masses (in MeV) predicted for the 2P($\frac{3}{2}$) levels of the B, D_s, and B_s systems. Underlined entries are Particle Data Group averages [9] used as inputs.

Meson Family	K	D	B	D_s	B_s
$M(1S)$	$\underline{794.3}$	$\underline{1973.2}$	$\underline{5313.1}$	$\underline{2074.9}$	5409.1[a]
Level Shift δ	0	32	42	56	67
$M(2^+(\frac{3}{2}))$	$\underline{1429 \pm 6}$	$\underline{2459.4 \pm 2.2}$	5767	2537	5846
$M(1^+(\frac{3}{2}))$	$\underline{1270 \pm 10}$	$\underline{2424 \pm 6}$	5755	2502	5834
$M(2^+(\frac{3}{2})) - M(1^+(\frac{3}{2}))$	159	35	12	35	12

[a] Assuming that $M(1S) = M(1S_0) + 34.5$ MeV, as in the B system. The pseudoscalar mass, $M_{B_s} = 5374.6$ MeV, is the weighted mean of the ALEPH and CDF values [10].

TABLE II. Decay rates of the 2P($\frac{3}{2}$) heavy-light mesons.

	Width (MeV)	
Transition	Calculated	Observed[a]
$D_2^*(2459) \to D^*\pi$	9[b]	
$D_2^*(2459) \to D\pi$	16[b]	
$D_2^*(2459) \to D\eta$	~ 0.1	
$D_2^*(2459) \to D\rho$	5 to 13	
$D_2^*(2459) \to$ all	30 to 38	19 ± 7
$D_1(2424) \to D^*\pi$	11 to 13	
$D_1(2424) \to D\rho$	8 to 11	
$D_1(2424) \to$ all	19 to 23	20^{+9}_{-5}
$D_{s2}^*(2537) \to D^*K$	2 to 4	
$D_{s2}^*(2537) \to DK$	6 to 7	
$D_{s2}^*(2537) \to D_s\eta$	~ 0.1	
$D_{s2}^*(2537) \to$ all	8 to 11	
$D_{s1}(2502) \to D^*K$	3 to 6	< 4.6
$B_2^*(5767) \to B^*\pi$	11	
$B_2^*(5767) \to B\pi$	10	
$B_2^*(5767) \to B^*\rho$	13 to 29	
$B_2^*(5767) \to B\rho$	4 to 13	
$B_2^*(5767) \to$ all	38 to 63	
$B_1(5755) \to B^*\pi$	14	
$B_1(5755) \to B^*\rho$	11 to 33	
$B_1(5755) \to B\rho$	6 to 8	
$B_1(5755) \to$ all	31 to 55	
$B_{s2}^*(5846) \to B^*K$	2 to 4	
$B_{s2}^*(5846) \to BK$	1 to 3	
$B_{s2}^*(5846) \to$ all	3 to 7	
$B_{s1}(5834) \to B^*K$	1 to 3	
$K_2^*(1429) \to K^*\pi$	16 to 22	25
$K_2^*(1429) \to K\pi$	35 to 40	50
$K_2^*(1429) \to K\rho$	10 to 19	9
$K_2^*(1429) \to K\omega$	2 to 4	3
$K_2^*(1429) \to$ all	63 to 85	
$K_1(1270) \to K^*\pi$	12 to 21	14
$K_1(1270) \to K\rho$	38[c]	38
$K_1(1270) \to K\omega$	9	10
$K_1(1270) \to$ all	59 to 68	

[a] 1992 Particle Data Group values [9].

[b] Sum fixed at 25 MeV.

[c] Input value.

TABLE III. Properties of the 3D($\frac{5}{2}$) heavy-light mesons.

State	Mass (MeV)	Width (MeV)
K_3^*	1770	170 to 182
K_2	1770	102 to 126
D_3^*	2830	324 to 479
D_2	2830	192 to 279
D_{s3}^*	2880	103 to 114
D_{s2}	2880	75 to 97
B_3^*	6148	285 to 387
B_2	6148	264 to 372
B_{s3}^*	6198	121 to 142
B_{s2}	6198	109 to 133