Properties of Orbitally Excited Heavy-Light $(Q\bar{q})$ Mesons

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Orbitally excited heavy-light $(Q\bar{q})$ 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 dramatically 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 an undetected neutrino. In hadron colliders and Z^0 factories, kinematic tagging may make practical high-statistics determinations of the form factors in semileptonic weak decay, and enable precise measurements of V_{cb} and V_{ub} [4,5].

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 $m_b \gg \Lambda_{\rm QCD}$, 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

$$M(nL_J(j_q)) = M(1S) + E(nL(j_q)) + \frac{C(nL_J(j_q))}{m_Q}\ , \quad (1)$$

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 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

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

where we have suppressed the j_q label for brevity. Upon identifying $E(2P)_D = E(2P)_K - \delta$, where $\delta = 32$ MeV is

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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].

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. 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 [9,15] at 2536.5 ± 0.8 MeV. We take the discrepancy between calculated and observed masses as a measure of the limitations of our method.

The $2P(\frac{1}{2})$ 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 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 $L_J(j_q)$, to a heavy-light meson $H'(L'_{J'}(j'_q))$, 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 becomes 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 $\mathcal{A}_R$ times a normalized 6-j symbol,

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

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

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

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 $\mathcal{A}_R$ 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 modified Gaussian form

$$F^{j_q,j'_q}_{j_h,\ell}(p^2) = F^{j_q,j'_q}_{j_h,\ell}(0) \exp(-p^2/\kappa^2) \left[\frac{M_\rho^2}{M_\rho^2 + p^2}\right]^\ell, \qquad (4)$$

and determine the overall strength of the decay and the momentum scale κ by fitting existing data. The final factor moderates the p^ℓ threshold behavior of the decay amplitude at high momenta [17].

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 $2P(\frac{3}{2}) \to 1S(\frac{1}{2}) + \pi$ 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 pionic transitions between the $2P(\frac{3}{2})$ and $1S(\frac{1}{2})$ multiplets. The results are shown in Table II; the predicted

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	
$D_2^*(2459) \to D^*\rho$	3	
$D_2^*(2459) \to D\rho$	< 1	
$D_2^*(2459) \to$ all	28	19 ± 7
$D_1(2424) \to D^*\pi$	11	
$D_1(2424) \to D^*\rho$	< 1	
$D_1(2424) \to D\rho$	6	
$D_1(2424) \to$ all	18	20^{+9}_{-5}
$D_{s2}^*(2537) \to D^*K$	< 1	
$D_{s2}^*(2537) \to DK$	7	
$D_{s2}^*(2537) \to D_s\eta$	~ 0.1	
$D_{s2}^*(2537) \to$ all	7	
$D_{s1}(2502) \to D^*K$	< 1	< 4.6
$B_2^*(5767) \to B^*\pi$	11	
$B_2^*(5767) \to B\pi$	10	
$B_2^*(5767) \to B^*\rho$	3	
$B_2^*(5767) \to B\rho$	< 1	
$B_2^*(5767) \to$ all	24	
$B_1(5755) \to B^*\pi$	16	
$B_1(5755) \to B^*\rho$	1	
$B_1(5755) \to B\rho$	3	
$B_1(5755) \to$ all	20	
$B_{s2}^*(5846) \to B^*K$	< 1	
$B_{s2}^*(5846) \to BK$	1	
$B_{s2}^*(5846) \to$ all	2	
$B_{s1}(5834) \to B^*K$	< 1	
$K_2^*(1429) \to K^*\pi$	12	25
$K_2^*(1429) \to K\pi$	27	50
$K_2^*(1429) \to K\rho$	12	9
$K_2^*(1429) \to K\omega$	3	3
$K_2^*(1429) \to$ all	55	
$K_1(1270) \to K^*\pi$	6	14
$K_1(1270) \to K\rho$	38^{c}	38
$K_1(1270) \to K\omega$	7	10
$K_1(1270) \to$ all	51	

[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	190
K_2	1770	100
D_3^*	2830	240
D_2	2830	140
D_{s3}^*	2880	100
D_{s2}	2880	60
B_3^*	6148	180
B_2	6148	170
B_{s3}^*	6198	100
B_{s2}	6198	90

rates are stable as the momentum scale κ ranges from 0.8 to 1.2 GeV. SU(3) determines the strengths of K and η transitions [18]. The predictions agree well with what is known about the $L = 1$ D and D_s states [19]. 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, $2.1 \pm 0.6 \pm 0.6$ [20].

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 consistent with 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 somewhat lower than the experimental values, but the ratios agree well 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 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. Rates for $K^{**} \to K\omega$ decays follow by SU(3) symmetry.

The results collected in Table II show that both the B_2^* and the B_1 states should be narrow, 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 $L = 2$ 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 [21]. 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 $D^{***}(2830)$, $B^{***}(6148)$, $D_s^{***}(2880)$, and

$B_s^{***}(6198)$ systems.

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 (≈ 175 MeV), but decay with about 20% probability to B_s and B_s^* by emitting a kaon. 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 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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