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Orbital excitations of heavy-light mesons in the coupling channel model

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The mass shifts of the P-wave D_s and B_s mesons are calculated in the coupling channel model using the effective chiral Lagrangian, which is deduced from QCD and does not contain fitting parameters. The strong mass shifts down due to coupling to DK and BK channels for 0^+ and $1^{+\prime}$ states have been obtained, while $1^{+\prime\prime}$ and 2^+ states remain almost at rest. The experimental limit on the width $\Gamma(D_{s1}(2536)) < 2.3$ MeV puts strong restrictions on the admissible mixing angle between the 1^+ and $1^{+\prime}$ states. The masses of 0^+ and $1^{+\prime}$ states of B_s mesons have been predicted.

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The experimental discovery of the orbitally-excited heavy-light $D_s(2317)$ and $D_s(2460)$ mesons [1] aroused a great interest for particle physicists. The masses of these states proved to be much lower than expected values in ordinary quark models while their widths were surprisingly small. The problem was studied in different approaches: in relativistic quark model calculations [2]–[4], on the lattice [5], in QCD Sum Rules [6, 7], in chiral models [8, 9] (for reviews see also [10, 11]). Note, that the masses of $D_s(0^+)$ and $D_s(1^{+'})$ in closed-channel approximation typically exceed by ~ 140 and 90 MeV their experimental numbers, so a multi-channel approach has to be applied to solve this problem.

The mass shifts of the $D_s(0^+, 1^{+'})$ mesons have already been considered in a number of papers with the use of unitarized coupled-channel model [12], in nonrelativistic Cornell model [13], in semi-relativistic model with inverse heavy quark mass expansion [14], and in different chiral models [15]–[17]. Here we address again this problem with the aim to calculate also the mass shifts of the $D_s(1^{+'})$ and $B_s(0^+, 1^{+'})$ states and the widths of the 2^+ and 1^+ states, following the approach developed in [16]. The main theoretical goal is to understand dynamical mechanism responsible for such large mass shifts of the 0^+ and $1^{+'}$ levels and explain why the position of other two levels remains practically unchanged.

Our analysis of the two-channel system is performed with the use of the chiral quark-pion Lagrangian which has been derived directly from the QCD Lagrangian [18] in the frame of the Field Correlator Method (FCM) and does not contain fitting parameters, so that the shift of the $D_s^*(0^+)$ state ~ 140 MeV is only determined by the conventional decay constant f_K.

From the common point of view, due to spin-orbit and tensor interactions the P-wave multiplet of a heavy-light (HL) meson is split into four levels with $J^P = 0^+, 1^+_L, 1^+_H, 2^+$ [19]. Here we use the notation H(L) for the higher (lower) 1^+ state because a priori one cannot say which of them mostly consists of the light quark $j = 1/2$ contribution. Starting with the Dirac's P-wave levels, one has the states with $j = 1/2$ and $j = 3/2$, which are not mixed in the heavy-quark limit, while for finite m_Q they can be mixed even in closed-channel approximation [8, 19]. The corresponding $1^+_{L,H}$ eigenstates can be obviously parameterized by the mixing angle ϕ.

Taking the meson emission to the lowest order, one obtains the effective quark-pion Lagrangian in the form

$$\Delta L_{FCM} = -\int \psi_i^+(x)\sigma|\mathrm{x}|\gamma_5 \frac{\varphi_a \lambda_a}{f_\pi} \psi_k(x) d^4x. \tag{1}$$

Writing the equation (1) as $\Delta L_{FCM} = -\int V_{if} dt$, one obtains the operator matrix element for the transition from the light quark state i (i.e. the initial state i of a HL meson) to the continuum state f with the emission of a NG meson $(\varphi_a \lambda_a)$. Thus we are now able to write the coupled channel equations, connecting any state of a HL meson to a decay channel which contains another HL meson plus a NG meson.

In subsequent analysis it is convenient to define the masses we are calculating with respect to nearby threshold: $m_{\mathrm{thr}} = m_K + m_D$. We introduce the following notations:

$$E_0 = m^{(0)}[D_s] - m_D - m_K, \quad \delta m = m[D_s] - m^{(0)}[D_s], \quad \Delta = E_0 + \delta m = m[D_s] - m_D - m_K, \tag{2}$$

where Δ determines the deviation of the D_s meson mass from the threshold, and can be complex if a decay to DK pair is allowed. In what follows we consider unperturbed masses $m_0(J^P)$ of the $(Q\bar{q})$

levels as given (our results do not change if we slightly vary their position, in this way the analysis is actually model-independent).

In our approximation we do not take into account the final state interaction in the DK system and neglect the D-meson motion. Also, in the w.f. we neglect possible (very small) mixing between the $D(1^-_{1/2})$, $D(1^-_{3/2})$ states and between $D_s(2^+_{3/2})$, $D_s(2^+_{5/2})$ states; physical $D_s(1^+)$ states can be mixed, though. For a HL meson we consider a light q (or strange s) quark with current (pole) mass $m_{q,s}$ moving in the static field of a heavy antiquark $\bar{Q}$, and take its w.f. as a 4-spinor obeying the Dirac equation with the linear scalar potential and the vector Coulomb potential with frozen $\alpha_s = \text{const}$:

$$U = \sigma r, \quad V_C = -\frac{\beta}{r}, \quad \beta = \frac{4}{3}\alpha_s. \tag{3}$$

The light quark eigenfunction is calculated numerically with the following set of parameters: (the same as in our previous papers [20]):

$$\sigma = 0.18 \text{ GeV}^2, \quad \alpha_s = 0.39, \quad m_s = 210 \text{ MeV}, \quad m_q \sim 0 \text{ MeV}, \tag{4}$$

The choice of σ and α_s is a common one in the frame of the FCM approach, and the value of the light quark mass really does not influence here on any physical results because of its smallness in comparison with the natural mass scale $\sqrt{\sigma}$. The strange quark mass is taken from [21], where it was found from the ratio of experimentally measured decay constants $f(D_s)/f(D)$; the same value can be obtained by a renormalization group evolution starting from the conventional value $m_s(2 \text{ GeV}) = 90 \pm 15$ GeV.

In our analysis the 4-component (Dirac) structure of the light quark w.f. is crucially important. In the end, it is just the strong overlap between higher and lower components of the quark bispinor which leads to the large shift of the $1^{+\prime}$ state with a concurrent small one for $1^{+\prime\prime}$ state, so this phenomena reveals a natural explanation (all the details can be found in [22]).

To compute the physical meson masses we will take into account the following pairs of mesons in coupled channels (i refers to first (initial) channel, while f refers to second (decay) one):

i	f
$D_s(0^+)$	$D(0^-) + K(0^-)$
$D_s(1^+)$	$D^*(1^-) + K(0^-)$
$D_s(2^+)$	$D^*(1^-) + K(0^-)$

(5)

and analogously for B-meson case, with corresponding masses and threshold values (in MeV):

$$\begin{aligned} m_{D^+} = 1869, \quad m_{D^+} + m_{K^-} = 2363; \qquad m_{D^{*+}} = 2010, \quad m_{D^{*+}} + m_{K^-} = 2504; \\ m_{B^+} = 5279, \quad m_{B^+} + m_{K^-} = 5772; \qquad m_{B^*} = 5325, \quad m_{B^*} + m_{K^-} = 5819. \end{aligned} \tag{6}$$

The ultimate results of our calculations are presented in Tables 1–3. A priori one cannot say whether the $|j = \frac{1}{2}\rangle$ and $|j = \frac{3}{2}\rangle$ states are mixed or not. If there is no mixing at all, in this case the width $\Gamma(D_{s1}(2536)) = 0.3$ MeV is obtained in [23], while the experimental limit is $\Gamma < 2.3$ MeV [24] and recently in [25] the width $\Gamma = 1.0 \pm 0.17$ MeV has been measured. Therefore small mixing is not excluded and here we take the mixing angle ϕ slightly deviated from $\phi = 0°$ (no

Table 1: $D_s(0^+)$-meson mass shift due to the DK decay channel and $B_s(0^+)$-meson mass shift due to the BK decay channel (all in MeV)

state	$m^{(0)}$	$m^{(\mathrm{theor})}$	$m^{(\mathrm{exp})}$	δm
$D_s(0^+)$	2475 (30)	2330(20)	2317	-145
$B_s(0^+)$	5814(15)	5709 (15)	not seen	-105

Table 2: The $D_s(1^+)$, $D_s(2^+)$ meson mass shifts and widths due to the D^*K decay channel for the mixing angle 4° (all in MeV)

state	$m^{(0)}$	$m^{(\mathrm{theor})}$	$m^{(\mathrm{exp})}$	$\Gamma^{(\mathrm{theor})}_{(D^*K)}$	$\Gamma^{(\mathrm{exp})}_{(D^*K)}$	δm
$D_s(1^+_H)$	2568(15)	2458(15)	2460	$\times$	$\times$	-110
$D_s(1^+_L)$	2537	2535	2535(1)	1.1	< 1.3	-2
$D_s(2^+_{3/2})$	2575	2573	2573(2)	0.03	not seen	-2

Table 3: The $B_s(1^+)$, $B_s(2^+)$ meson mass shifts and widths due to the B^*K decay channel for the mixing angle 4° (all in MeV)

state	$m^{(0)}$	$m^{(\mathrm{theor})}$	$m^{(\mathrm{exp})}$	$\Gamma^{(\mathrm{theor})}_{(B^*K)}$	$\Gamma^{(\mathrm{exp})}_{(B^*K)}$	δm
$B_s(1^+_H)$	5835(15)	5727(15)	not seen	$\times$	$\times$	-108
$B_s(1^+_L)$	5830	5828	5829 (1)	0.8	< 2.3	-2
$B_s(2^+_{3/2})$	5840	5838	5839(1)	$< 10^{-3}$	not seen	-2

mixing case). Then we define those angles ϕ which are compatible with experimental data for the masses and widths of both 1^+ states.

The large value $\cos^2\phi$ for the $1^+_H(j = 1/2)$ state provides large mass shift (~ 100 MeV) of this level and at the same time does not produce the mass shift of the 1^+_L level, which is almost pure $j = \frac{3}{2}$ state. We would like to stress here that the mass shifts weakly differ for D_s and B_s, or, in other words, weakly depend on the heavy quark mass.

Thus we have obtained the shifted masses $M(B_s, 0^+) = 5710(15)$ MeV and $M(B_s, 1^{+'}) = 5730(15)$ MeV, which are in agreement with the predictions in [11] and of S.Narison [7] and by ~ 100 MeV lower than in [2],[8]. The masses of the 2^+ and 1^+ states precisely agree with experiment.

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