Two topics for a discussion on the $b\bar{s}$ and $b\bar{q}$ systems

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The analysis of the $b\bar{s}$ system is an important issue in the Physics programs of the hadron colliders. We discuss two different topics: the structure of the orbitally excited states and prediction of the rates of a class of nonleptonic $B_s$ decays.

Experiments at the hadron colliders can analyze different aspects of the heavy meson systems, both in the strong, both in the weak sector. For such systems, predictions are possible using symmetries and the available data. We present two examples of experimental interest: the properties of the orbitally excited $b\bar{s}$ ($b\bar{q}$) resonances and the rates of a class of nonleptonic $B_s$ decays.

1. PROPERTIES OF ORBITALLY EXCITED $b\bar{s}$, $b\bar{q}$ STATES

A theoretical framework to describe the excited $b\bar{s}$, $b\bar{q}$ states is the heavy quark chiral effective theory, constructed using the spin-flavour symmetry for hadrons comprising a single heavy quark, in the $m_Q \to \infty$ limit, and the chiral symmetry valid in the massless limit for light quarks [1]. Heavy $Q\bar{q}$ mesons are classified in doublets according to the angular momentum $s_\ell$ of the light degrees of freedom: $s_\ell = s_\bar{q} + \ell (s_\bar{q})$ is the light antiquark spin, $\ell$ the orbital angular momentum of the light degrees of freedom relative to the heavy quark) [2]. For $\ell = 0$ the $S^P = \frac{1}{2}^-$ doublet comprises two states with $J^P = (0^-,1^-)$: $P = D(s_0)B(s_0)$ and $P^* = D^*_s(s_0)B^*_s(s_0)$ mesons in case of charm (beauty), respectively. For $\ell = 1$ it could be either $S^P = \frac{1}{2}^+$ or $S^P = \frac{3}{2}^+$. The two corresponding doublets have $J^P = (0^+,1^+)$ and $J^P = (1^+,2^+)$. We denote the $J^P_{s_\ell} = (0^+,1^+)$'s as $(P^0_0, P^0_1)$ and the $J^P_{s_\ell} = (1^+,2^+)$'s as $(P_1, P_2)$. The negative and positive parity doublets are described by the fields $H_a$, $S_a$ and $T^a_\mu$ ($a = u, d, s$ is a light flavour index): $H_a = \frac{1+\xi}{2}[P^a_\mu \gamma^\mu - P_\mu s_\gamma^5]$, $S_a = \frac{1+\xi}{2}[P^a_{\mu\nu}\gamma^\mu - P^a_{\nu\mu}]$, $T^a_\mu = \frac{1+\xi}{2}\left\{P^a_{\mu\nu}\gamma^\nu - P_{\mu\nu}\sqrt{\frac{3}{2}}\gamma^5 \left[\gamma^\mu - \frac{1}{2}\gamma^5 \gamma^\nu \gamma^\mu - \gamma^\nu \gamma^\mu \right]\right\}$, with the various operators annihilating mesons of four-velocity $v$.

The octet of light pseudoscalar mesons is introduced using $\xi = e^{\frac{2\pi}{3}}$ and $\Sigma = \xi^2$; the matrix $\mathcal{M}$ contains $\pi, K$ and $\eta$ fields:

$$
\mathcal{M} = \begin{pmatrix}
\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \frac{\pi^+}{\sqrt{2}} & K^+ \\
\pi^- - \frac{\eta}{\sqrt{6}} & \frac{\eta}{\sqrt{2}} & K^0 \\
\bar{K}^0 & K^0 & -\frac{\sqrt{2}}{2} \eta
\end{pmatrix}
$$

with $f_\pi = 132$ MeV. The effective QCD Lagrangian is constructed imposing invariance under heavy quark spin-flavour transformations and chiral transformations. The kinetic term

$$
\mathcal{L} = i \text{Tr}\left\{\tilde{H}_b v^\mu D_{\mu ba} H_a \right\} + \frac{f_\pi^2}{8} \text{Tr}\left\{\partial^\mu \Sigma \partial_\mu \Sigma^\dagger\right\} + \text{Tr}\left\{S_b \left( i\, v^\mu D_{\mu ba} - \delta_{ba} \Delta_S\right) S_a \right\} + \text{Tr}\left\{T^b_\mu \left( i\, v^\mu D_{\mu ba} - \delta_{ba} \Delta_T\right) T_{a\mu} \right\}
$$

(2)

(with $D_{\mu ba} = -\delta_{ba} \partial_\mu + \frac{1}{2} \left(\xi^1 \partial_\mu \xi + \xi \partial_\mu \xi^1\right)_b$ and $A_{\mu ba} = \frac{1}{2} \left(\xi^1 \partial_\mu \xi - \xi \partial_\mu \xi^1\right)_b$) involves the mass splittings $\Delta_S$ and $\Delta_T$ between positive and negative parity doublets. They can be expressed in terms of the spin-averaged masses: $\Delta_S = \overline{M}_S - \overline{M}_H$ and $\Delta_T = \overline{M}_T - \overline{M}_H$, with $\overline{M}_H = (3M_{P^*} + M_P)/4$, $\overline{M}_S = (3M_{P^*_1} + M_{P^*_0})/4$ and $\overline{M}_T = (5M_{P^*_2} + 3M_{P^*_1})/8$.

At the leading order in the heavy quark expansion the decays $H \to H' M$, $S \to H'M$ and $T \to H'M$ ($M$ a light pseudoscalar meson) are
Other two effects due to spin symmetry-breaking

\[ M_{h} = \frac{1}{2m_{Q}} \left\{ \lambda_{H} T r[H_{\alpha} H_{\beta} \gamma_{5} A_{\mu}^{b \nu}] + h c \right\} \]

\[ \lambda_{H} = \frac{1}{2m_{Q}} \right\{ \lambda_{H} T r[H_{\alpha} \sigma^{\mu \nu} H_{\beta} \sigma^{\mu \nu}] + \lambda_{S} T r[S_{\alpha} \sigma^{\mu \nu} S_{\beta} \sigma^{\mu \nu}] + \lambda_{T} T r[T^\alpha_{\mu} \sigma^{\mu \nu} T^\alpha_{\nu} \sigma^{\mu \nu}] \right\} \]

with \( \lambda_{H,S,T} \) related to the hyperfine mass splittings:

\[ \lambda_{H} = (M_{P_{1}} - M_{P_{0}}) / 8, \quad \lambda_{S} = (M_{P_{2}} - M_{P_{0}}) / 8, \quad \lambda_{T} = 3 (M_{P_{2}} - M_{P_{1}}) / 8. \]

Other two effects due to spin symmetry-breaking concern the possibility that the members of the states could also decay in S wave into the lowest lying heavy mesons and pseudoscalars, and that a mixing may be induced between the two 1^+ states belonging to the two positive parity doublets with different \( s_{t} \).

The corresponding terms in the effective Lagrangian are:

\[ \mathcal{L}_{D_{1}} = \frac{f}{2m_{Q} \Lambda_{X}} T r[H_{\alpha} \sigma^{\mu \nu} T^{\mu}_{\alpha} \sigma^{\mu \nu} \gamma_{5}(i D_{\theta} A_{\theta} + i D_{\theta} A_{\theta}) + h c] \]

\[ \mathcal{L}_{mix} = \frac{g_{1}}{2m_{Q}} T r[S_{\alpha} \sigma^{\mu \nu} T_{\mu \alpha} \sigma^{\mu \nu} v^{\alpha}] + h c \]
collected in Table 2, can be obtained if the splittings $\Delta S$ and $\Delta T$ are the same for charm and beauty, which is true in the rigorous heavy quark limit; at $O(1/m_Q)$ this corresponds to assuming that the matrix element of the kinetic energy operator is the same for the three doublets. $B_{s0}^*$ and $B_{s1}^*$ turn out to be below the $BK$ and $B^*K$ thresholds, therefore they are expected to be narrow \[10,7\]. Preliminary data are available from Tevatron: $M(B_1) = 5734 \pm 3 \pm 2$ MeV and $M(B_2^*) = 5738 \pm 5 \pm 1$ MeV (CDF), and $M(B_1) = 5720.8 \pm 2.5 \pm 5.3$ MeV and $M(B_2^*) - M(B_1) \approx 25.2 \pm 3.0 \pm 1.1$ MeV (D0), together with $M(B_{s2}^*) = 5839.1 \pm 1.4 \pm 1.5$ MeV (D0) \[11\].

The $B_2^* - B_1$ mass splitting measured by D0 is compatible with the prediction. The difference between the predicted and the measured masses is of order $O(\Lambda^2/\mu_K^2)$, i.e. of the size of the terms neglected in the calculation.

The couplings $h'$ and $f$ in eqs. (3) can be obtained from the widths of the two members of the $s^0$ doublet, $D_1$ and $D_2$, and those of charmed-strange meson transitions: $D_2^{*+} \to D^{(*)0}K^0$, $D^{(*)0}K^+$ and $D_1^{*+} \to D^{(*)+}K^0$, $D^{(*)+}K^+$. We use recent data from Belle Collaboration [5]: $\Gamma(D_2^{*+}) = 45.6 \pm 4.4 \pm 6.5 \pm 1.6$ MeV, $\Gamma(D_1^{*+}) = 23.7 \pm 2.7 \pm 0.2 \pm 4.0$ MeV, together with $h = -0.56$ [12], a theoretical estimate coinciding with the value obtained from the width of $D_0^*$.

A further constraint is the Belle measurement of the helicity angle distribution in the decay $D_{s1}(2536) \to D^{(*)+}K^0$, with the determination of the ratio $R = \frac{\Gamma_S}{\Gamma_S + \Gamma_D}$, $\Gamma_S,D$ being the S and D wave partial widths, respectively \[13\]: $0.277 \leq R \leq 0.955$. Taking into account all the constraints, we get:

$$h' = 0.45 \pm 0.05 \quad f = 0.044 \pm 0.044 \text{ GeV}. \quad (7)$$

The coupling constant $f$ is compatible with zero, indicating that the contribution of the Lagrangian term (5) is small. Since also the coupling $g_1$ turns out to be small, the two $1^+$ states corresponding to the $s^0$ doublet $\frac{1^+}{2} \cdot \frac{3^+}{2}$ practically coincide with the physical states. We obtain $\Gamma(D_{s1}(2536)) = 2.5 \pm 1.6$ MeV and the widths of excited $B_{(s)}$ mesons in Table 3. A word of caveat is needed here, since these predictions are obtained only considering the heavy quark spin-symmetry breaking terms in the effective Lagrangian; corrections due to spin-symmetric but heavy flavour breaking terms involve addi-

| Table 2 | Predicted masses of excited beauty mesons. |
|---------|----------------|
| $B_{(s)0}^*(0^+)$ | $B_{(s)1}^*(1^+)$ | $B_{(s)1}^*(1^+)$ | $B_{(s)2}^*(2^+)$ |
| $b\bar{q}$ | $5.70 \pm 0.025 \text{ GeV}$ | $5.75 \pm 0.03 \text{ GeV}$ | $5.774 \pm 0.002 \text{ GeV}$ | $5.790 \pm 0.002 \text{ GeV}$ |
| $b\bar{s}$ | $5.71 \pm 0.03 \text{ GeV}$ | $5.77 \pm 0.03 \text{ GeV}$ | $5.877 \pm 0.003 \text{ GeV}$ | $5.893 \pm 0.003 \text{ GeV}$ |

| Table 3 | Decay widths and branching fractions of $J^{PC} = (1^+, 2^+)_{\frac{1}{2}}$ beauty mesons obtained using the theoretical masses. To compute the full widths we assume saturation of the two-body modes. |
|---------|----------------|
| $B_2^{*0} \to B^{0+}\pi^-$ | $20 \pm 5$ | 0.34 | $B_2^{*0} \to B^{*0}K^-$ | $4 \pm 1$ | 0.37 |
| $B_2^{*0} \to B^0\pi^0$ | $10.0 \pm 2.3$ | 0.17 | $B_2^{*0} \to B^0K^0$ | $4 \pm 1$ | 0.34 |
| $B_2^{*0} \to B^{++}\pi^-$ | $18 \pm 4$ | 0.32 | $B_2^{*0} \to B^{*+}K^-$ | $1.7 \pm 0.4$ | 0.15 |
| $B_2^{*0} \to B^{*0}\pi^+$ | $9.3 \pm 2.2$ | 0.16 | $B_2^{*0} \to B^{*0}K^0$ | $1.5 \pm 0.4$ | 0.13 |
| $B_2^{*0}$ | $57.3 \pm 13.5$ | | $B_2^{*0}$ | $11.3 \pm 2.6$ | |
| $B_1^0 \to B^{0+}\pi^-$ | $28 \pm 6$ | 0.66 | $B_3^{*0} \to B^{*+}K^-$ | $1.9 \pm 0.5$ | 0.54 |
| $B_1^0 \to B^{0}\pi^0$ | $14.5 \pm 3.2$ | 0.34 | $B_3^{*1} \to B^{*0}K^0$ | $1.6 \pm 0.4$ | 0.46 |
| $B_1^0$ | $43 \pm 10$ | | $B_3^{*1}$ | $3.5 \pm 1.0$ | |
tudes that can be constrained, both in moduli and in the
those collected in Table 4. They are governed,
quark transitions belonging to the octet in the final state, there
ing transitions with a light pseudoscalar meson
pseudoscalar meson. The predicted $B_s^+$ branching fractions are also reported.

### 2. A CLASS OF $B_s$ DECAYS BY AN SU(3) ANALYSIS

Coming to weak interaction processes, it is again possible to exploit the idea of using a symmetry and the experimental data to make predictions [15]. In this case, the symmetry is $SU(3)_F$ and the predictions concern the rates of a class of $B_s$ decay modes, an important topic for the $B_s$ physics programs at the Tevatron and at the LHC. We consider the modes induced by the quark transitions $b \rightarrow c\bar{u}d$ and $b \rightarrow c\bar{u}s$, namely those collected in Table 4. They are governed, in the $SU(3)_F$ limit, by few independent amplitudes that can be constrained, both in moduli and phase differences, from $B$ decay data. Considering transitions with a light pseudoscalar meson belonging to the octet in the final state, there are three different topologies in decays induced by $b \rightarrow c\bar{u}d(s)$, the color allowed topology $T$, the color suppressed topology $C$ and the $W$-exchange topology $E$. The transition in the $SU(3)$ singlet $\eta_0$ involves another amplitude $D$, not related to the previous ones. The identification of the different amplitudes can be done observing that $\bar{B} \rightarrow DP$ decays induced by $b \rightarrow c\bar{u}q$ ($q = d$ or $s$) involve a weak Hamiltonian transforming as a flavor octet: $H_{W} = V_{cb}V_{us}T_{(8)} + V_{cb}V_{us}^T(\frac{1}{2} + \frac{1}{2})$ (denoting by $T_{(\nu)}^{(\mu)}$ the $\nu = (Y, I_3)$ component of an irreducible tensor operator of rank $(\mu)$). When combined with the initial $\bar{B}$ mesons, which form a (3’s)-representation of $SU(3)$, this leads to (3’s), (6) and (15’s) representations. These are also the representations formed by the combination of the final octet light pseudoscalar meson and triplet D meson. Therefore, the three reduced amplitudes are $\langle \phi^{(\nu)}|T^{(8)}|B^{(3’s)}\rangle$, with $\mu = 3’s, 6, 15’s$ [16]. Linear combinations of the reduced amplitudes produce the three topological diagrams.

The four $\bar{B} \rightarrow D\pi$ and $\bar{B} \rightarrow D_sK$ rates cannot determine $C$, $T$, $E$ and their phase differences [17]. $\bar{B} \rightarrow D_sK$ only fixes the modulus of $E$, which is sizeable. Moreover, the presence of $E$ does not allow to directly relate the amplitudes $T$ or $C$ in $D\pi$ and $DK$. However, all the information on $\bar{B} \rightarrow D\pi, D_sK$ and $DK$ can be used to tightly determine $T$, $C$ and $E$. In Fig[14] the allowed regions in the $C/T$ and $E/T$ planes are depicted. The phase differences between the various amplitudes are large, showing deviation from naive (or
generalized) factorization, providing constraints to QCD-based approaches to non leptonic $B$ decays \cite{18} and suggesting sizeable long-distance effects \cite{19}. Fixing $|V_{us}/V_{ud}| = 0.226 \pm 0.003$, we obtain $|\frac{C}{T}| = 0.53 \pm 0.10$, $|\frac{E}{T}| = 0.115 \pm 0.020$, $\delta_C - \delta_T = (76 \pm 12)^\circ$ and $\delta_E - \delta_T = (112 \pm 46)^\circ$. With the resulting amplitudes we can predict the rates of $B_s$ decays in Table 4. The uncertainties in the predicted rates are small, even in the $W$-exchange induced processes. The dots are the result of the fit.

$$\frac{\Gamma(B_s \rightarrow D_s^- \pi^+)}{\Gamma(B^0 \rightarrow D^- \pi^+)} = 1.32 \pm 0.18 \pm 0.38 \ [20].$$

The decays into $\eta$ or $\eta'$ involve the amplitude $D$ corresponding to the transition in the $SU(3)$ singlet $\eta_0$, and the $\eta - \eta'$ mixing angle $\theta$. Fixing $\theta = -15.4^\circ$, we obtain $|\frac{C}{T}| = 0.41 \pm 0.11$ and $\delta_D - \delta_T = -(25 \pm 51)^\circ$, and the rates of corresponding $B_s$ modes.

Among other $b \rightarrow c d l(s)$ induced modes, we consider those into $D_{(s)}V$, $D_{(s)}P$, with the same $SU(3)$ decomposition as in Table 4. $B$ decay data are collected in Table 5 including the recently observed $W$-exchange mode $B^0 \rightarrow D_s^+ K^-$, together with the predictions for $B_s$. Present experimental data for other modes induced by the same quark transitions, namely $B \rightarrow D_{(s)}V$ decays, are not precise enough to constrain the independent $SU(3)$ amplitudes.

$SU(3)_F$ breaking can modify the predictions: its effects are not universal and in general cannot be reduced to well defined and predictable patterns. Its parametrization introduces additional quantities that at present cannot be sensibly bounded since they are obscured by the experimental uncertainties. It will be interesting to investigate its role when other $B_s$ decay rates will be measured and more precise $B$ branching fractions will be available.

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| $B^-$, $\bar{B}^+$ | BR (exp) | $\bar{B}^+$ | BR (th) |
|------------------|--------|--------------|---------|
| $D_0^\rho^-$     | $(1.34 \pm 0.18) \times 10^{-2}$ | $D_0^\rho^+$ | $(7.2 \pm 3.5) \times 10^{-3}$ |
| $D_0^{\rho^0}$   | $(2.9 \pm 1.1) \times 10^{-4}$ | $D_0^{\rho^0}$ | $(9.6 \pm 2.4) \times 10^{-4}$ |
| $D_+^{\rho^-}$   | $(7.7 \pm 1.3) \times 10^{-3}$ | $D_+^{\rho^-}$ | $(5.0 \pm 2.8) \times 10^{-4}$ |
| $D_+K^-$         | $< 9.9 \times 10^{-4}$ | $D_+K^-$ | $(4.5 \pm 3.1) \times 10^{-4}$ |
| $D_0^{K^*+}$     | $(6.1 \pm 2.3) \times 10^{-4}$ | $D_0^{K^*+}$ | $(0.28 \pm 1.4) \times 10^{-4}$ |
| $D_0^{K^*0}$     | $(4.8 \pm 1.2) \times 10^{-5}$ | $D_0^{K^*0}$ | $(5.2 \pm 2.8) \times 10^{-4}$ |
| $D_+^{K^*+}$     | $(3.7 \pm 1.8) \times 10^{-4}$ | $D_+^{K^*+}$ | $(4.5 \pm 3.1) \times 10^{-4}$ |
| $D_0^{*\pi^-}$   | $(4.6 \pm 0.4) \times 10^{-3}$ | $D_0^{*\pi^-}$ | $(3.2 \pm 0.2) \times 10^{-3}$ |
| $D_0^{0\pi^0}$   | $(2.7 \pm 0.5) \times 10^{-4}$ | $D_0^{0\pi^0}$ | $(4.7 \pm 2.2) \times 10^{-4}$ |
| $D_+^{\pi^-}$    | $(2.76 \pm 0.21) \times 10^{-3}$ | $D_+^{\pi^-}$ | $(5.7 \pm 1.7) \times 10^{-7}$ |
| $D_0^*K^-$       | $(2.0 \pm 0.6) \times 10^{-5}$ | $D_0^*K^-$ | $(1.1 \pm 3.4) \times 10^{-7}$ |
| $D_0^{0K^-}$     | $(3.6 \pm 1.0) \times 10^{-4}$ | $D_0^{0K^-}$ | $(1.3 \pm 0.2) \times 10^{-4}$ |
| $D_+^{KK^-}$     | $(2.0 \pm 0.5) \times 10^{-4}$ | $D_+^{KK^-}$ | $(1.3 \pm 0.2) \times 10^{-4}$ |

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