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New Spectroscopy of Heavy Mesons

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I discuss the most recently discovered open charm mesons, both with and without strangeness. By exploiting the heavy quark limit, strong decay widths of such mesons are computed. Comparison between theoretical predictions and experimental measurements are useful to assign the right quantum numbers to such states. As for hidden charm mesons, I consider the case of X(3872). Analysis of its radiative decays to $J/\psi\gamma$ and $\psi(2S)\gamma$ shows the plausibility of the identification with $\chi_{c1}(2P)$.

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1. Introduction

Starting from 2003, several new hadrons have been discovered. Many of them have been easily classified, having properties consistent with the predictions of the quark model. For many others the identification is not straightforward, due to their peculiar features. Here I consider charmed mesons and, in particular, I discuss how the use of the heavy quark limit can help classifying the most recently discovered states. I first discuss open charm mesons and in the last part of this paper I also briefly consider mesons with hidden charm, with particular attention to the $X(3872)$.

In the $c\bar{s}$ case, well established states are the pseudoscalar $D_s(1968)$ and vector $D_s^*(2112)$ mesons, s-wave states of the quark model, as well as the axial-vector $D_{s1}(2536)$ and tensor $D_{s2}(2573)$ mesons, p-wave states. Two states with $J^P = 0^+$, 1^+ were discovered in 2003 [1, 2]: $D_{sJ}(2317)$ and $D_{sJ}^*(2460)$. Their classification was not easy due to their puzzling properties: they are very narrow and were observed through the isospin violating modes $D_{sJ}(2317) \to D_s\pi^0$ and $D_{sJ}^*(2460) \to D_s^*\pi^0$. Indeed their masses are below the DK, D^*K thresholds that would have allowed them to decay conserving isospin and this may explain why they are so narrow. Analysis of their radiative decays shows that their interpretation as ordinary $c\bar{s}$ mesons completing the p-wave multiplet is consistent with data[3] and is now widely accepted.

More recently discovered $c\bar{s}$ states are $D_{sJ}(2860)$ and $D_{sJ}(2700)$, observed decaying to DK by BaBar [4] and Belle [5] Collaborations, respectively. In the case of $D_{sJ}(2700)$ spin-parity was fixed to $J^P = 1^-$. From the analysis in [6] it seems likely that it is the first radial excitation of D_s^*, as will be discussed in Section 3. In [6] the state $D_{sJ}(3040)$ was also observed. After introducing in Section 2 heavy meson spectroscopy in the heavy quark limit, I report in Section 3 the predictions for the decays of these three states in such a limit and discuss the implications for their classification.

As for charmed non strange states, the most recent discoveries are $D(2550)^0$, $D^*(2600)^{\pm,0}$, $D(2750)^0$ and $D^*(2760)^{\pm,0}$, observed by BaBar Collaboration. They are the subject of Section 4.

The case of hidden charm mesons and, in particular, of X(3872) is considered in Section 5.

2. Heavy meson spectroscopy in the heavy quark limit

In this Section I consider heavy-light $Q\bar{q}$ mesons, where Q is a heavy quark, having mass $m_Q \gg \Lambda_{QCD}$ and $\bar{q}$ is a light antiquark: $q = u,d,s$. In the heavy quark (HQ) limit $m_Q \to \infty$ the heavy quark decouples from the light degrees of freedom, i.e. the light antiquark and gluons. There are two main implications of such a decoupling. First, the spin s_Q of the heavy quark and the total angular momentum of the light degrees of freedom s_ℓ are separately conserved in strong interactions. As a consequence, heavy hadrons can be classified according to the value of s_ℓ and collected in doublets comprising two states with total spin $J = s_\ell \pm \frac{1}{2}$ and parity $P = (-1)^{\ell+1}$. ℓ is the orbital angular momentum of the light degrees of freedom, so that $\vec{s}_\ell = \vec{\ell} + \vec{s}_q$, s_q being the light antiquark spin. The second consequence is that the flavour of the heavy quark becomes irrelevant. One can conclude that in the HQ limit heavy quark spin-flavour symmetries arise. Spin symmetry predicts that the two states in a doublet are degenerate; flavour symmetry relates the properties of the states having the same quantum numbers and differing only for the flavour of the heavy quark.

In order to classify the newly discovered states, it is useful to consider the strong decays of the heavy mesons to light pseudoscalar mesons, because the decay rates of these processes depend on the quantum numbers of the decaying mesons. To this aim, I use an effective lagrangian approach where the octet of light pseudoscalar mesons and the various heavy meson doublets are described by effective fields. The lagrangian is built in such a way to be invariant under heavy quark spin-flavour transformations and chiral transformations of the light pseudo Goldstone boson fields.

Let us consider the doublets corresponding to $\ell = 0,1,2$. The doublet with the lowest lying states is obtained in correspondence to $\ell = 0$ and has $s_\ell^P = \frac{1}{2}^-$. Its members have spin-parity $J^P = (0^-,1^-)$ and I denote them (P,P^*). The effective field describing this doublet is named H_a, ($a = u,d,s$ a light flavour index). $\ell = 1$ leads to $s_\ell^P = \frac{1}{2}^+$ or $s_\ell^P = \frac{3}{2}^+$, hence to two doublets of states having $J^P = (0^+,1^+)$ and $J^P = (1^+,2^+)$. I denote such mesons as (P_0^*,P_1'), described by the field S_a, and (P_1,P_2^*), described by the field T_a, respectively. Other two doublets are obtained when $\ell = 2$, having $s_\ell^P = \frac{3}{2}^-$ or $s_\ell^P = \frac{5}{2}^-$; their members are denoted by (P_1^*,P_2), with effective field X_a, and $(P_2'^*,P_3)$, with effective field X_a', respectively. Analogous notation is used in the case of the radial excitations of such fields: I add a tilde for distinction ($\tilde{P}$, $\tilde{P}^*$, ...).

The expressions for the effective fields are:

$$
\begin{aligned}
H_a &= \frac{1+\not v}{2}[P^*_{a\mu}\gamma^\mu - P_a\gamma_5] \\
S_a &= \frac{1+\not v}{2}\left[P'^{\mu}_{1a}\gamma_\mu\gamma_5 - P^*_{0a}\right] \\
T_a^\mu &= \frac{1+\not v}{2}\left\{P^{\mu\nu}_{2a}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\} \\
X_a^\mu &= \frac{1+\not v}{2}\left\{P^{*\mu\nu}_{2a}\gamma_5\gamma_\nu - P'^*_{1a\nu}\sqrt{\frac{3}{2}}\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu + v^\mu)\right]\right\} \\
X_a'^{\mu\nu} &= \frac{1+\not v}{2}\left\{P^{\mu\nu\sigma}_{3a}\gamma_\sigma - P^{*'\alpha\beta}_{2a}\sqrt{\frac{5}{3}}\gamma_5\left[g^\mu_\alpha g^\nu_\beta - \frac{1}{5}\gamma_\alpha g^\nu_\beta(\gamma^\mu - v^\mu) - \frac{1}{5}\gamma_\beta g^\mu_\alpha(\gamma^\nu - v^\nu)\right]\right\} .
\end{aligned}
\tag{2.1}
$$

The various operators in the previous expressions annihilate mesons of four velocity v, conserved in strong interactions, contain a factor $\sqrt{m_Q}$ and have dimension $3/2$. In order to describe the octet of light pseudoscalar mesons I introduce the definition $\xi = e^{\frac{i\mathscr{M}}{f_\pi}}$, $\Sigma = \xi^2$, with the matrix $\mathscr{M}$ containing π, K and η fields ($f_\pi = 132$ MeV):

$$
\mathscr{M} = \begin{pmatrix} \sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}}\pi^0 + \sqrt{\frac{1}{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}
\tag{2.2}
$$

In terms of these fields one can build effective Lagrangian terms describing the decays $F \to H\pi$ ($F = H,S,T,X,X'$, M denoting generically a light pseudoscalar meson) at leading order in the heavy quark mass and light meson momentum expansion [7]:

$$
\begin{aligned}
\mathscr{L}_H &= g\,Tr\left[\bar{H}_a H_b \gamma_\mu\gamma_5 \mathscr{A}^\mu_{ba}\right] \\
\mathscr{L}_S &= h\,Tr\left[\bar{H}_a S_b \gamma_\mu\gamma_5 \mathscr{A}^\mu_{ba}\right] + h.c. \\
\mathscr{L}_T &= \frac{h'}{\Lambda_\chi}Tr\left[\bar{H}_a T^\mu_b (iD_\mu \not{\mathscr{A}} + i\not D \mathscr{A}_\mu)_{ba}\gamma_5\right] + h.c.
\end{aligned}
$$

$$\mathscr{L}_X = \frac{k'}{\Lambda_\chi} Tr\Big[\bar{H}_a X^\mu_b (iD_\mu \not{\mathscr{A}} + i\not{D} \mathscr{A}_\mu)_{ba}\gamma_5\Big] + h.c. \tag{2.3}$$
$$\mathscr{L}_{X'} = \frac{1}{\Lambda_\chi{}^2} Tr\Big[\bar{H}_a X'^{\mu\nu}_b \big[k_1\{D_\mu, D_\nu\}\mathscr{A}_\lambda + k_2(D_\mu D_\lambda \mathscr{A}_\nu + D_\nu D_\lambda \mathscr{A}_\mu)\big]_{ba}\gamma^\lambda\gamma_5\Big] + h.c.$$

$\Lambda_\chi \simeq 1$ GeV is the chiral symmetry-breaking scale. g, h, h' k', k_1, k_2 (I put $k = k_1 + k_2$) are effective coupling constants. The decays described by $\mathscr{L}_S$ and $\mathscr{L}_T$ occur in $s-$ and $d-$ wave, respectively; on the other hand, the transitions described by $\mathscr{L}_X$ and $\mathscr{L}_{X'}$ occur in $p-$ and $f-$ wave. The structure of the analogous Lagrangian terms for radial excitations of the various doublets is the same, except that one has to replace the various coupling constants by new ones, denoted by $\tilde{g}$, $\tilde{h}$, ...

Determinations of the various couplings constants exist. g could be determined from the transitions $D^*_{(s)} \to D\pi(K)$. From the experimental branching fractions and total width of $D^{*\pm}$ [8] one obtains $g = 0.64 \pm 0.075$, a value larger than predictions obtained in the HQ limit [9, 10, 11]. Determinations of h have been obtained using QCD sum rules [10] in the HQ limit and also recently by lattice [11]. Predictions for the other couplings can be found in [12].

In the next Section I use this approach to try to identify the newly discovered $c\bar{s}$ mesons.

3. Exploiting the heavy quark limit to classify $D_{sJ}(2860)$, $D_{sJ}(2700)$ and $D_{sJ}(3040)$

$D_{sJ}(2860)$ was observed in 2006 by BaBar Collaboration decaying to D^0K^+ and D^+K_S. Mass and width were measured: $M = 2856.6 \pm 1.5 \pm 5.0$ MeV, $\Gamma = 47 \pm 7 \pm 10$ [4]. On the other hand, $D_{sJ}(2700)$ was discovered by Belle Collaboration [5] studying the D^0K^+ invariant mass distribution in $B^+ \to \bar{D}^0 D^0 K^+$, with $M = 2708 \pm 9^{+11}_{-10}$ MeV, $\Gamma = 108 \pm 23^{+36}_{-31}$ MeV and $J^P = 1^-$.

A possibility to identify $D_{sJ}(2860)$ and $D_{sJ}(2710)$ has been put forward in [13], based on the calculation of their strong decay widths in the HQ limit under different assignments for their quantum numbers. I present below a summary of such analyses.

Possible identifications for $D_{sJ}(2860)$ should take into account that it decays to DK. Among the states with radial quantum number $n = 1$ this is possible only for the $J^P = 1^-$ state of the $s_\ell^P = \frac{3}{2}^-$ doublet, or for the $J^P = 3^-$ state of the $s_\ell^P = \frac{5}{2}^-$ one. As for radial excitations with $n = 2$, allowed identifications are those with the first radial excitation of D^*_s ($J^P = 1^-$ $s_\ell^P = \frac{1}{2}^-$) or of $D_{sJ}(2317)$ ($J^P = 0^+$ $s_\ell^P = \frac{1}{2}^+$) or of $D^*_{s2}(2573)$ ($J^P = 2^+$ $s_\ell^P = \frac{3}{2}^+$).

The situation is simpler for $D_{sJ}(2710)$. since it has $J^P = 1^-$ it can be identified only with the first radial excitation in the $s_\ell^P = \frac{1}{2}^-$ doublet ($D^{*\prime}_s$) or with the low lying state with $s_\ell^P = \frac{3}{2}^-$ (D^*_{s1}).

Quantities that are sensitive to the quantum numbers of the decaying mesons are the ratios $R_1 = \frac{\Gamma(D_{sJ} \to D^*K)}{\Gamma(D_{sJ} \to DK)}$ and $R_2 = \frac{\Gamma(D_{sJ} \to D_s\eta)}{\Gamma(D_{sJ} \to DK)}$ ($D^{(*)}K = D^{(*)+}K_S + D^{(*)0}K^+$). These can be computed using the effective lagrangian (2.4), with the results reported in Table 1 [13]. Noticeably, $R_{1,2}$ are independent on the coupling constants in the effective lagrangians, greatly reducing the model dependence of the result. Among the various options for $D_{sJ}(2860)$, the assignment $s_\ell^p = \frac{5}{2}^-$, $J^P = 3^-$, $n = 1$ seems the most likely one. In this case the small DK width is due to the kaon momentum suppression factor: $\Gamma(D_{sJ} \to DK) \propto q_K^7$ reflecting the fact that the transition occurs in f-wave. An argument supporting this identification is that if $D_{sJ}(2860)$ has $J^P = 3^-$, it is not expected to be produced in $B \to DD_{sJ}(2860)$ decays and indeed no signal of $D_{sJ}(2860)$ was found studying the $B^+ \to \bar{D}^0 D^0 K^+$ Dalitz plot [5]. Among the other identifications, the decay to D^*K

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$D_{sJ}(2860)$	R_1	R_2
$s_\ell^p = \frac{1}{2}^-, J^P = 1^-, n = 2$	1.23	0.27
$s_\ell^p = \frac{1}{2}^+, J^P = 0^+, n = 2$	0	0.34
$s_\ell^p = \frac{3}{2}^+, J^P = 2^+, n = 2$	0.63	0.19
$s_\ell^p = \frac{3}{2}^-, J^P = 1^-, n = 1$	0.06	0.23
$s_\ell^p = \frac{5}{2}^-, J^P = 3^-, n = 1$	0.39	0.13
$D_{sJ}(2710)$	R_1	R_2
$s_\ell^p = \frac{1}{2}^-, J^P = 1^-, n = 2$	0.91	0.20
$s_\ell^p = \frac{3}{2}^-, J^P = 1^-, n = 1$	0.043	0.163

Table 1: Predicted ratios R_1 and R_2 (see text for definitions) for the various assignment of quantum numbers to $D_{sJ}(2860)$ and $D_{sJ}(2710)$.

is not possible for the state with $J^P = 0^+$. Therefore, this option has been excluded when in a subsequent experimental study the decay $D_{sJ}(2860) \to D^* K$ was observed [6]. However, the measurement of the ratio R_1 [6]

$$\frac{BR(D_{sJ}(2860) \to D^* K)}{BR(D_{sJ}(2860) \to DK)} = 1.10 \pm 0.15_{stat} \pm 0.19_{syst} \tag{3.1}$$

leaves the identification of $D_{sJ}(2860)$ still unclear. Support to the hypothesis that $D_{sJ}(2860)$ is a $J^P = 3^-$ state could be gained if its non-strange partner D_3, that can also be produced in B decays [14], were observed with similar features. In particular, it should be narrow, too.

The case of $D_{sJ}(2710)$ seems to be easier. As one can argue by looking at Table 1, the best way to distinguish among the two possible identifications for this meson is to measure the ratio R_1. This was done by BaBar Collaboration [6] with the result

$$\frac{BR(D_{sJ}(2710) \to D^* K)}{BR(D_{sJ}(2710) \to DK)} = 0.91 \pm 0.13_{stat} \pm 0.12_{syst} \; . \tag{3.2}$$

Comparison with the prediction in Table 1 shows that $D_{sJ}(2710)$ is most likely $D_s^{*\prime}$.

I now discuss $D_{sJ}(3040)$, a broad state decaying to $D^* K$ and not to DK having $M = 3044 \pm 8_{stat}(^{+30}_{-5})_{syst}$ MeV and $\Gamma = 239 \pm 35_{stat}(^{+46}_{-42})_{syst}$ MeV [6]. The observed decay mode suggests that it has unnatural parity: $J^P = 1^+, 2^-, 3^+, \cdots$. Among the states with $n = 1$ it could be only one of the two states D_{s2} and $D_{s2}^{\prime *}$ having both $J^P = 2^-$ and belonging to the doublets with $s_\ell = 3/2$ and $s_\ell = 5/2$, respectively. As for radial excitations ($n = 2$), allowed candidates are the two $J^P = 1^+$ mesons: $\tilde{D}'_{s1}$, belonging to the doublet with $s_\ell = 1/2$ and $\tilde{D}_{s1}$, belonging to the doublet with $s_\ell = 3/2$. However, if $D_{sJ}(2860)$ were experimentally confirmed as the $J^P_{s_\ell} = 3^-_{5/2}$ meson, it would be unlikely that $D_{sJ}(3040)$ were its spin partner $D_{s2}^{*\prime}$ with $J^P_{s_\ell} = 2^-_{5/2}$, since this would imply an unlikely mass inversion in a spin doublet. Also the identification with D_{s2} would be disfavored, even though in that case the two mesons would belong to different doublets.

The mass of $D_{sJ}(3040)$ is large enough to allow several decay modes. Decay to a charmed meson and a light pseudoscalar one can be evaluated using the effective Lagrangians in Eq.(2.4), from which it is possible to compute the ratio $R_1 = \frac{\Gamma(D_{sJ}(3040) \to D_s^* \eta)}{\Gamma(D_{sJ}(3040) \to D^* K)}$ ($D^* K = D^{*0} K^+ + D^{*^+} K_S^0$).

decay modes	$\tilde{D}'_{s1}$ (n=2) ($J^P_{s_\ell}=1^+_{1/2}$)	$\tilde{D}_{s1}$ (n=2) ($J^P_{s_\ell}=1^+_{3/2}$)	D_{s2} (n=1) ($J^P_{s_\ell}=2^-_{3/2}$)	$D^{*\prime}_{s2}$ (n=1) ($J^P_{s_\ell}=2^-_{5/2}$)
D^*K, $D^*_s\eta$	$s-$ wave	$d-$ wave	$p-$ wave	$f-$ wave
R_1	0.34	0.20	0.245	0.143
D^*_0K, $D^*_{s0}\eta$, D'_1K	$p-$ wave	$p-$ wave	$d-$ wave	$d-$ wave
D_1K	$p-$ wave	$p-$ wave	-	$d-$ wave
D^*_2K	$p-$ wave	$p-$ wave	$s-$ wave	$d-$ wave
DK^*, $D_s\phi$	$s-$ wave	$s-$ wave	$p-$ wave	$p-$ wave
	$\Gamma\simeq 140$ MeV	$\Gamma\simeq 20$ MeV	negligible	negligible

Table 2: Features of the decay modes of $D_{sJ}(3040)$ for the four proposed assignments.

$D_{sJ}(3040)$ can also decay to $(D^*_0,D'_1)K$, $(D_1,D^*_2)K$ and $D^*_{s0}\eta$, as well as to DK^* or $D_s\phi$; these modes can be also described using effective lagrangian approaches [15]. The results for the various transitions obtained in the four possible identifications are collected in Table 2 [16], allowing to draw some conclusions. Looking at the wave in which their decays proceed, one can infer that the two $J^P=1^+$ should be broader than the two $J^P=2^+$ states, hence $D_{sJ}(3040)$ should more likely be identified with one of such two axial-vector mesons. Dinstiction between these is provided by the widths to the DK^* and $D_s\phi$ decay modes which are larger for $\tilde{D}'_{s1}$ than for $\tilde{D}_{s1}$.

4. Newly discovered $c\bar{q}$ mesons

BaBar Collaboration [17] has observed four new structures in the process $e^+e^-\to c\bar{c}\to D^{(*)}\pi X$: $D^0(2550)$ decaying to $D^{*+}\pi^-$; $D^{*0}(2600)$ decaying to $D^+\pi^-$ and $D^{*+}\pi^-$ and $D^{*+}(2600)$ decaying to $D^0\pi^+$; $D^{*0}(2760)$ decaying to $D^+\pi^-$ and $D^{*+}(2760)$ decaying to $D^0\pi^+$; $D^{*0}(2750)$ decaying to $D^{*+}\pi^-$. The ratio were also measured:

$$\frac{\mathscr{B}(D^{*0}(2600)\to D^+\pi^-)}{\mathscr{B}(D^{*0}(2600)\to D^{*+}\pi^-)}=0.32\pm0.02\pm0.09\;. \tag{4.1}$$

In the case of the final state $D^{*+}\pi^-$, performing angular analysis BaBar Collaboration has argued that $D^0(2550)$ has $J^P=0^+$ while $D^*(2600)$ has natural parity; this is consistent with the observation of both the decays to $D\pi$ and $D^*\pi$. The consequent conclusions drawn in [17] are that $(D(2550),D^*(2600))$ are most likely identified with the $J^P=(0^-,1^-)$ doublet of $n=2$ radial excitations of (D,D^*) mesons, while $(D(2750),D^*(2760))$ could be $\ell=2$, $n=1$ states.

Following [12], I discuss the case of $D^*(2600)$, for which the measurement eq. (4.1) is available. There are four states that can decay both to $D\pi$ and $D^*\pi$. The first is $\tilde{D}^*$: BaBar Collaboration suggests the identification with this state, mainly because its mass is consistent with what one expects for the non strange partner of $D_{sJ}(2700)$, already identified with $\tilde{D}^*_s$.

However, the calculation of the ratio in (4.1) for $\tilde{D}^*$, assigning it the mass of 2600 MeV and using the same approach described in the previous Section, gives [12]:

$$\frac{\mathscr{B}(\tilde{D}^{*0}(2600)\to D^+\pi^-)}{\mathscr{B}(\tilde{D}^{*0}(2600)\to D^{*+}\pi^-)}=0.822\pm0.003\;. \tag{4.2}$$

The discrepancy with the datum (4.1) might suggest to consider other possibilities for $D^*(2600)$: D_1^* in X, D_3 in X' and $\tilde{D}_2^*$ in $\tilde{T}$ for which the decays to $D\pi$ and $D^*\pi$ are both allowed. Indeed, in no case the experimental ratio is reproduced, suggesting that either the approach based on the HQ limit should be improved or that a revision of the experimental analysis is required.

5. Hidden charm mesons: The case of X(3872)

A large number of new heavy quarkonium or quarkonium-like states has also been observed in the last decade, many of which have not been clearly identified [18]. One of these is $X(3872)$, discovered in 2003 by Belle Collaboration in $B^\pm \to K^\pm X \to K^\pm J/\psi\pi^+\pi^-$ decays [19] and confirmed by several other experiments [20]. The parameters of this resonance are $M(X) = 3871.57 \pm 0.25$ MeV and $\Gamma(X) < 2.3$ MeV (90/% C.L.) [8]. The search for charged partners in the $J/\psi\pi^\pm\pi^0$ channel produced no result [21], while the decay $X \to J/\psi\gamma$ was observed, allowing to fix $C = +1$.

Moreover, the measurement $\frac{B(X\to D^0\bar{D}^0\pi^0)}{B(X\to J/\psi\pi^+\pi^-)} = 9\pm 4$, [22] shows that X mainly decays into final states with open charm mesons. The measurement that poses a problem with the identification of X with a charmonium state is $\frac{B(X\to J/\psi\pi^+\pi^-\pi^0)}{B(X\to J/\psi\pi^+\pi^-)} = 1.0\pm 0.4\pm 0.3$ [23] which implies, if the two modes are induced by ρ^0 and ω intermediate states, isospin violation. However, in order to correctly understand the large ratio $\frac{B(X\to J/\psi\pi^+\pi^-\pi^0)}{B(X\to J/\psi\pi^+\pi^-)}$ one has to consider that phase space effects in two and three pion modes are very different so that the isospin violating amplitude is 20% of the isospin conserving one [24]. As for the spin-parity of X, on the one hand the angular analysis in $X \to J/\psi\pi^+\pi^-$ favours $J^P = 1^+$, on the other the study the three pion distribution in $X \to J/\psi\omega \to J/\psi\pi\pi\pi$ seems more favourable to $J^P = 2^-$ [25]. Therefore, possible charmonium options for X are either the state $\chi_{c1}(2P)$, the first radial excitation of χ_{c1},or the state η_{c2} having $J^{PC} = 2^{-+}$.

Among the exotic interpretations, the coincidence between the mass $M(D^{*0}\overline{D}^0) = 3871.2\pm 1.0$ MeV and the mass of X, has lead to the conjecture that $X(3872)$ could be a $D^{*0}\overline{D}^0$ molecule [26, 27]. In this case, the wave function of $X(3872)$ might be enriched of several hadronic components [28] explaining why it has no definite isospin. Since the molecular binding mechanism still needs to be clearly identified, it is interesting to consider the HQ limit predictions in the case of an ordinary charmonium state for the ratio of the radiative decay rates of $X(3872)$ to $J/\psi\gamma$ and $\psi(2S)\gamma$, for which experimental data exist. In [29] this has been done assuming that $X(3872)$ is the state $\chi_{c1}(2P)$ and using an approach based on an effective lagrangian exploiting only spin symmetry for heavy $Q\bar{Q}$ states [30] since in heavy quarkonia there is no heavy flavour symmetry [31].

I adopt the notation $n^{2s+1}L_J$ to identify a heavy $Q\bar{Q}$ state ($Q = c, b$) with parity $P = (-1)^{L+1}$ and charge-conjugation $C = (-1)^{L+s}$: n is the radial quantum number, L the orbital angular momentum, s the spin and J the total angular momentum.

If X is the state $\chi_{c1}(2P)$, it belongs to the $L = 1$ multiplet described by the effective field:

$$P^{(Q\bar{Q})\mu} = \left(\frac{1+\not{v}}{2}\right)\left(\chi_2^{\mu\alpha}\gamma_\alpha + \frac{1}{\sqrt{2}}\varepsilon^{\mu\alpha\beta\gamma}v_\alpha\gamma_\beta\chi_{1\gamma} + \frac{1}{\sqrt{3}}(\gamma^\mu - v^\mu)\chi_0 + h_1^\mu\gamma_5\right)\left(\frac{1-\not{v}}{2}\right) \quad (5.1)$$

where the fields χ_2, χ_1, χ_0 correspond to the spin triplet with $J^{PC} = 2^{++}, 1^{++}, 0^{++}$, respectively, while the spin singlet h_1 has $J^{PC} = 1^{+-}$.

J/ψ and $\psi(2S)$ are described by the $J^P = 1^-$ H_1 component of the doublet:

$$J = \frac{1+\not{v}}{2}\left[H_1^\mu\gamma_\mu - H_0\gamma_5\right]\frac{1-\not{v}}{2} \; . \quad (5.2)$$

The effective Lagrangian describing radiative transitions among members of the P wave and of the S wave multiplets is [30]:

$$\mathscr{L}_{nP\leftrightarrow mS} = \delta_Q^{nPmS} Tr\left[\bar{J}(mS) J_\mu(nP)\right] v_\nu F^{\mu\nu} + \text{h.c.}. \tag{5.3}$$

$F^{\mu\nu}$ the electromagnetic field strength tensor. Hence, a single constant δ_Q^{nPmS} describes all the transitions among the members of the nP multiplet and those of the mS one.

The ratios $R_J^{(b)} = \frac{\Gamma(\chi_{bJ}(2P)\to\Upsilon(2S)\gamma)}{\Gamma(\chi_{bJ}(2P)\to\Upsilon(1S)\gamma)}$, proportional to $R_\delta^{(b)} = \frac{\delta_b^{2P1S}}{\delta_b^{2P2S}}$ $(J=0,1,2)$, have been measured [8], providing the average value $R_\delta^{(b)} = 8.8\pm 0.7$. Even though the couplings might be different in the beauty and the charm cases, it is reasonable that their ratios stay stable. As a consequence, one can use the result for $R_\delta^{(b)}$ in the case of $\chi_{c1}(2P)$ obtaining:

$$R_1^{(c)} = \frac{\Gamma(\chi_{c1}(2P)\to\psi(2S)\gamma)}{\Gamma(\chi_{c1}(2P)\to\psi(1S)\gamma)} = 1.64\pm 0.25\,. \tag{5.4}$$

This should be compared to the datum in [32] [1]:

$$R_X = \frac{\Gamma(X(3872)\to\psi(2S)\gamma)}{\Gamma(X(3872)\to\psi(1S)\gamma)} = 3.5\pm 1.4\,. \tag{5.5}$$

Considering the underlying approximation, the experimental result in (5.5) and the determination in (5.4) provide a consistency argument for the identification $X(3872)=\chi_{c1}(2P)$, while composite scenarios predict that the rate of $X(3872)\to\psi(2S)\gamma$ should be suppressed compared to $X(3872)\to\psi(1S)\gamma$ [34, 35].

6. Conclusions

The use of the HQ limit allows to classify mesons with a single heavy quark in doublets. In the case of charm, many states fit in the resulting scheme. In order to properly classify some newly discovered states, I exploited an effective lagrangian approach to compute the ratios of strong decay widths depending on the quantum numbers of decaying state. Comparison with the predictions for such ratios allows to conclude that $D_{sJ}(2700)$ is most likely the first radial excitation of D_s^*, while more investigation is required in the case of $D_{sJ}(2860)$ and of $D^*(2600)$. The application of a similar approach to open charm meson, and in particular to radiative decays of $X(3872)$ shows that identification of this state with $\chi_{c1}(2P)$ is plausible.

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