Interpretation of $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$

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Abstract — The experimental status of the recently observed resonances which could be interpreted as $c\bar{q}$ mesons with $s_P^l = \frac{1}{2}^+$ is reviewed. In the framework of HQET and chiral perturbation theory, strong and radiative widths of these states are computed in the hypothesis that they are $c\bar{q}$ states, obtaining results consistent with the experimental measurements. Masses and widths for the analogous states containing a beauty quark are also predicted.

1 Introduction

Let us consider a meson containing a single heavy quark $Q$. In the infinite heavy quark mass limit the heavy quark spin $S_Q$ and the total angular momentum of light degrees of freedom $s_l = L + S_Q$ decouple. Therefore $Q\bar{q}$ mesons can be classified in doublets labelled by $s_l$ and parity eigenvalues, the members of which are degenerate in mass. In the lowest lying states the orbital angular momentum of light degrees of freedom is $L=0$ and it results $s_l = \frac{1}{2}$. The corresponding doublet is composed by two states with $J_{s_l}^P = (0^-, 1^-)_{\frac{1}{2}}$. For $L=1$ we have the $s_l^P = \frac{1}{2}^+$ and $s_l^P = \frac{3}{2}^+$ doublets, with $J_{s_l}^P = (0^+, 1^+)_{\frac{1}{2}}$ and $J_{s_l}^P = (1^+, 2^+)_{\frac{3}{2}}$, respectively.

Let us focus on the case of charmed mesons and denote the members of the positive parity doublets as: $(0^+, 1^+)_{\frac{1}{2}} = (D_{(s)}^*, D_{(s)1})$ and $(1^+, 2^+)_{\frac{3}{2}} = (D_{(s)}1, D_{(s)2}^*)$. Conservation of parity, total angular momentum and heavy quark spin require that the strong decays $D(s_l^P = \frac{3}{2}^+) \rightarrow D(s)\pi$ proceed via a d-wave transition while the decays $D(s_l^P = \frac{1}{2}^+) \rightarrow D(s)\pi$ proceed via an s-wave transition. As a consequence, the states with $s_l^P = \frac{1}{2}^+$ are expected to be broad, whereas those with $s_l^P = \frac{3}{2}^+$ are presumably narrow.

Last year some resonances were discovered which could be interpreted as $s_l^P = \frac{1}{2}^+$ states of $c\bar{q}$ and $c\bar{s}$ systems. These states constitute the subject of this talk. The non strange resonances are detected with broad width, as expected, whereas those with strangeness are observed to be very narrow. The discrepancy has given rise to various interpretations. After a description of the recent experimental observations we shall discuss several interpretations of the detected resonances through the analysis of their decay modes.
2 Experimental observations

2.1 Broad $c\bar{c}$ states

Last year Belle observed two broad resonances containing a charm quark which could be identified as $s_{1}^{P} = \frac{1}{2}^{+}$ $c\bar{c}$ states [1]. These resonances are observed in $B \to D^{*+}\pi$ decays (where $D^{*+}$ indicates $L=1$ states) which have been studied using the $D^{+}\pi^{-}\pi^{-}$ and $D^{*+}\pi^{-}\pi^{-}$ final states. The Dalitz plot analysis carried out for the $D^\pi\pi$ final state includes the amplitude of the known $D^{*0}_2\pi^{-}$ mode, possible contributions of the processes with virtual $D^{*0}_2\pi^{-}$ and $B^{*0}_2\pi^{-}$ production and an intermediate $D\pi$ broad resonance with free mass and width and assigned $J^{P} = 0^{+}$ quantum numbers. A fit of the projection of the Dalitz plot to the $D\pi$ axis, where the pion is the one having the smallest momentum, favours the presence of the scalar contribution. A similar analysis is performed for the $D^{*+}\pi^{-}\pi^{-}$ final state, obtaining the evidence for a broad resonance with $J^{P} = 1^{+}$ quantum numbers. The $D\pi$ and $D^{*}\pi$ mass distributions are shown in Fig. 1, whereas the mass and width of the broad states obtained by the fit are collected in Table 1. An analogous study has been carried out by FOCUS Collaboration [2], which considered both the $D^{0}\pi^{+}$ and $D^{+}\pi^{-}$ charge configurations. Also in this case, a broad scalar contribution is requested in order to fit the $D\pi$ mass distribution. The values of mass and width quoted by FOCUS are collected in Table 1. Although the values obtained for the mass of the scalar state are rather different, presumably as a consequence of the difficulty in fitting a scalar component, we include in Table 1 the average of Belle and FOCUS data.

2.2 $D^{*}_{sJ}(2317)$ and $D_{sJ}(2460)$

Two narrow states have been observed with charm and strangeness, which could be interpreted as $s_{1}^{P} = \frac{1}{2}^{+}$ states. BaBar Collaboration discovered the narrow resonance $D^{*}_{sJ}(2317)$ in the $D_{s}\pi^{0}$ system [3], with mass close to 2.32 GeV and width consistent with the experimental resolution ($\sim 10$ MeV). This resonance, shown in Fig. 2, was confirmed by Belle [4], CLEO [5] and recently by FOCUS [6], with similar properties. FOCUS preliminary measurement of the mass is $M = 2323 \pm 2$ MeV,
Table 1: Masses and widths of broad resonances observed in $D\pi$ and $D^*\pi$ systems.

|          | Belle [1]       | FOCUS [2]       | Average   |
|----------|-----------------|-----------------|-----------|
| $D_{0}^{*0}$ | $M$ (MeV) 2308 ± 17 ± 15 ± 28 | $2407 ± 21 ± 35$ | 2351 ± 27 |
|          | $\Gamma$ (MeV) 276 ± 21 ± 18 ± 60 | 240 ± 55 ± 59 | 262 ± 51 |
| $D_{0}^{*+}$ | $M$ (MeV) 2407 ± 21 ± 15 ± 28 | 2403 ± 14 ± 35 |          |
|          | $\Gamma$ (MeV) 283 ± 24 ± 34 |          |          |
| $D_{1}^{0}$ | $M$ (MeV) 2427 ± 26 ± 20 ± 15 |          |          |
|          | $\Gamma$ (MeV) 384±107 ± 24 ± 70 |          |          |

Figure 2: Left: The $D_{s}^{+}\pi^{0}$ mass distribution for (a) the decay $D_{s}^{+} \rightarrow K^{+}K^{-}\pi^{+}$ and (b) the decay $D_{s}^{+} \rightarrow K^{+}K^{-}\pi^{+}\pi^{0}$ observed by BaBar [3]. Right: Distribution of (a) the masses $M(D_{s}\pi^{0})$ and (b) the mass differences $\Delta M(D_{s}\pi^{0}) = M(D_{s}\pi^{0}) - M(D_{s})$ for the $D_{s}\pi^{0}$ candidates in the decay $D_{s}^{+} \rightarrow K^{+}K^{-}\pi^{+}$, measured by CLEO [5].

slightly above the values reported in Table 2.

The occurrence of the decay in $D_{s}\pi^{0}$ implies that $D_{sJ}^{*}(2317)$ has natural spin-parity. Furthermore BaBar helicity analysis for this decay is consistent with spin 0 assignment to $D_{sJ}^{*}(2317)$ (Fig. 3), though such analysis does not rule out different possibilities since the same distribution could also result from an isotropic production polarization. Further support to the $J^{P} = 0^{+}$ hypothesis is the absence of a peak in the $D_{s}\gamma$ system.

CLEO discovered a narrow resonance in the $D_{sJ}^{*}\pi^{0}$ system [5], named $D_{sJ}(2460)$, soon confirmed by BaBar [8] and Belle [4]. The experimental values for mass and width are shown in Table 2. Belle also reports the first observation of the radiative decay $D_{sJ}(2460) \rightarrow D_{s}\gamma$ (Fig. 4), soon confirmed by BaBar. Belle and BaBar have observed the production of the $D_{sJ}$ states also from B decays [9]-[10], detecting clean signals for $B \rightarrow t\bar{t}D_{sJ}^{*}(2317)[D_{s}\pi^{0}]$, $B \rightarrow t\bar{t}D_{sJ}(2460)[D_{s}\pi^{0}]$ and $B \rightarrow t\bar{t}D_{sJ}(2460)[D_{s}\gamma]$ channels. Furthermore BaBar reports the observation of the analogous decay modes involving combinations of the $D_{sJ}$ with a neutral or charged $D^{*}$. The measured branching ratios are shown in Table 3.
Figure 3: BaBar helicity angle analysis of the decay $D_{sJ}^*(2317)\rightarrow D_s\pi^0$ [7]. Left: Uncorrected angular distribution. Center: Dependence of efficiency on angle. Right: Efficiency-corrected angular distribution.

The ratio $\frac{B(D_{sJ}(2460)\rightarrow D_s\gamma)}{B(D_{sJ}(2460)\rightarrow D_s^0\pi^0)}$ obtained by Belle from continuum analysis is $0.55\pm0.13\pm0.08$, whereas the corresponding value from B decays is $0.38\pm0.11\pm0.04$. BaBar preliminary analysis does not report a value for this quantity, yet. However using its measurements of single branching ratios and assuming that statistical and systematic errors are independent for each channel and among different channels, one obtains $\frac{B(D_{sJ}(2460)\rightarrow D_s\gamma)}{B(D_{sJ}(2460)\rightarrow D_s^0\pi^0)} = 0.44\pm0.17$, consistently with Belle measurements.

Table 2: Masses and widths of the narrow resonances $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ measured by BaBar, Belle and CLEO Collaborations. The average value for the mass is also reported.

| $D_{sJ}^*(2317)$ | $D_{sJ}(2460)$ | ref. |
|-----------|-------------|-----|
| M (GeV) | $\Gamma$ (GeV) | M (GeV) | $\Gamma$ (GeV) | |
| 2317.3 ± 0.4 ± 0.8 | < 10 | 2458.0 ± 1.0 ± 1.0 | < 10 | BaBar [3]-[8] |
| 2317.2 ± 0.5 ± 0.9 | < 4.6 | 2456.5 ± 1.3 ± 1.3 | < 5.5 | Belle [9] |
| 2318.5 ± 1.2 ± 1.1 | <7 | 2463.6 ± 1.7 ± 1.2 | <7 | CLEO [5] |
| 2317.4 ± 0.6 | | 2458.8 ± 1.0 | |

The $D_{sJ}(2460)\rightarrow D_s^0\pi^0$ decay implies that $D_{sJ}(2460)$ has unnatural spin-parity. The observation of its radiative decay in $D_s\gamma$ rules out the possibility that it is $J=0$, and helicity distribution measured by Belle and BaBar in B decays is consistent with $J=1$. These arguments supports $J^P = 1^+$ hypothesis.

3 Interpretations

Though states decaying via s-wave are expected to be broad, the strange resonances $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ have been detected with narrow widths. Such narrowness can be explained in the c\pi interpretation with the isospin violation occurring in the observed decays, which are the only two body strong decays kinematically allowed according to experimental masses. However, some potential models predict for these states masses above the thresholds of the isospin conserving decays in DK and $D^*K$, respectively for the $0^+$ and $1^+$ states, so that these states were expected as broad resonances in these systems [11]. Since potential models resulted rather accurate in reproducing the spectrum of other charmed mesons, this discrepancy has caused
candidates measured by Belle [9]: (a) \( D_s J^0(2317) \rightarrow D_s \pi^0 \), (b) \( D_s J^0(2460) \rightarrow D_s^* \pi^0 \) and (c) \( D_s J^0(2460) \rightarrow D_s \gamma \).

Figure 5: Helicity distribution of \( D_s J^0(2460) \rightarrow D_s \gamma \) measured by Belle [9] (left) and BaBar [10] (right). The distributions are consistent with the assignment \( J = 1 \) (continuous line in the left panel, first plot in the right panel), and not with \( J = 2 \) (dashed line in the left panel, second plot in the right panel).

different interpretations to be worked out. Barnes, Close and Lipkin propose a DK molecular state [12]; similarly, Szczepaniak suggests a \( D \pi \) atom [13]. H. Y. Cheng and W. S. Hou propose a 4-quark state [14] and Browder, Pakvasa and Petrov suggest that \( D_s J^0 \) states can be explained by a mixing of conventional p-wave \( c \bar{s} \) states with 4-quark states [15]. Since DK or \( D \pi \) bound states could have \( I=1 \), one should observe isospin partners of these states. CDF looks for such isospin partners in \( D_s \pi^- \) and \( D_s \pi^+ \) systems, without finding any peak near 2.32 GeV [16]. A further hypothesis is proposed by van Beveren and Rupp [17], who interpret \( D_s J^0(2317) \) as a quasi-bound scalar \( c \bar{s} \) state in a unitarized meson model taking into account the virtual DK scattering channel.

A way to try to identify the observed resonances is to compute their widths in the hypothesis that they are \( c \bar{q} \) states and compare the resulting predictions with the experimental values. In the following, we describe such a calculation. We should obtain widths of several hundreds MeV for non strange states and widths less than experimental resolution for states with strangeness.
Table 3: Branching fractions $\left(10^{-3}\right)$ measured by BaBar and Belle. Upper limits (at 90% C.L.) are shown in parentheses.

| Decay Mode | BaBar [10] | Belle [9] | Average |
|------------|------------|-----------|---------|
| $B^0 \to D_s^0 D^- (D^*_s \to D_s^+ \pi^0)$ | $2.09 \pm 0.40 \pm 0.34^{+0.10}_{-0.42}$ | $0.86 \pm 0.26^{+0.33}_{-0.26}$ | 1.09 ± 0.38 |
| $B^0 \to D_s^0 D^s^- (D^*_s \to D_s^+ \pi^0)$ | $1.12 \pm 0.38 \pm 0.20^{+0.37}_{-0.22}$ | — | — |
| $B^+ \to D_s^0 \overline{D}_s^0 (D_s^\ast \to D_s^+ \pi^0)$ | $1.28 \pm 0.37 \pm 0.22^{+0.42}_{-0.26}$ | $0.81 \pm 0.24^{+0.30}_{-0.27}$ | 0.94 ± 0.32 |
| $B^+ \to D_s^0 \overline{D}_s^0 (D_s^\ast \to D_s^+ \pi^0)$ | $1.91 \pm 0.84 \pm 0.50^{+0.63}_{-0.38}$ | — | — |
| $B^0 \to D_s^0 D^- (D^*_s \to D_s^+ \gamma)$ | — | $0.27^{+0.29}_{-0.22}$ (< 0.95) | — |
| $B^+ \to D_s^0 \overline{D}_s^0 (D^*_s \to D_s^+ \gamma)$ | — | $0.25^{+0.21}_{-0.16}$ (< 0.76) | — |
| $B^0 \to D'_s D^- (D'_s \to D_s^+ \pi^0)$ | $1.71 \pm 0.72 \pm 0.27^{+0.37}_{-0.35}$ | $2.27 \pm 0.68_{-0.62}^{+0.73}$ | 1.98 ± 0.69 |
| $B^0 \to D'_s D^s^- (D'_s \to D_s^+ \pi^0)$ | $5.89 \pm 1.24 \pm 1.16^{+1.96}_{-1.17}$ | — | — |
| $B^+ \to D'_s \overline{D}_s^0 (D'_s \to D_s^+ \pi^0)$ | $2.07 \pm 0.71 \pm 0.45^{+0.69}_{-0.41}$ | $1.19 \pm 0.36^{+0.61}_{-0.49}$ | 1.45 ± 0.59 |
| $B^+ \to D'_s \overline{D}_s^0 (D'_s \to D_s^+ \pi^0)$ | $7.30 \pm 1.68 \pm 1.68^{+2.40}_{-1.43}$ | — | — |
| $B^0 \to D'_s D^- (D'_s \to D_s^+ \gamma)$ | $0.92 \pm 0.24 \pm 0.11^{+0.30}_{-0.19}$ | $0.82 \pm 0.25_{-0.19}^{+0.22}$ | 0.86 ± 0.25 |
| $B^0 \to D'_s D^s^- (D'_s \to D_s^+ \gamma)$ | $2.60 \pm 0.39 \pm 0.34^{+0.56}_{-0.52}$ | — | — |
| $B^+ \to D'_s \overline{D}_s^0 (D'_s \to D_s^+ \gamma)$ | $0.80 \pm 0.21 \pm 0.12^{+0.26}_{-0.16}$ | $0.56 \pm 0.17^{+0.16}_{-0.15}$ | 0.63 ± 0.19 |
| $B^+ \to D'_s \overline{D}_s^0 (D'_s \to D_s^+ \gamma)$ | $2.26 \pm 0.47 \pm 0.43^{+0.74}_{-0.44}$ | — | — |
| $B^0 \to D'_s D^- (D'_s \to D_s^+ \gamma)$ | — | $0.13^{+0.20}_{-0.14}$ (< 0.6) | — |
| $B^+ \to D'_s \overline{D}_s^0 (D'_s \to D_s^+ \gamma)$ | — | $0.31^{+0.27}_{-0.23}$ (< 0.98) | — |

Furthermore for the latter we should obtain ratios of radiative and strong widths consistent with experimental measurements [18].

4 Strong decays

Low energy interactions between heavy mesons and light pseudoscalar mesons can be described by means of HQET and chiral perturbation theory. In the framework of HQET mesons containing a single heavy quark are classified in doublets the members of which are degenerate in mass. Introducing one field for each doublet, it is possible to build a lagrangian invariant respect to spin and flavour heavy quark transformations and respect to chiral transformations for the pseudo Goldstone K, π and η bosons [19]:

$$
\mathcal{L} = igTr\left\{\overline{H}_a H_b \gamma_\mu \gamma_5 A_\mu^{a \bar{a}}\right\} + ihTr\left\{S_b \gamma_\mu \gamma_5 A_\mu^{a \bar{a}} \overline{H}_a\right\} + i\frac{h'}{\Lambda}\overline{H}_b T_{\mu \lambda} \gamma_5 (D_\mu A^\lambda)_{ba} \overline{H}_a + h.c. + \ldots
$$

(1)

where H, S and T represent $\frac{1}{2}^-$, $\frac{1}{2}^+$ and $\frac{3}{2}^+$ doublets, respectively. These fields are defined by the following expressions:

$$
H_a = \frac{1}{2} \left[ P_a \gamma_\mu - P_a \gamma_5 \right]
$$

(2)

$$
S_a = \frac{1}{2} \left[ P_1 a \gamma_\mu \gamma_5 - P_a \right]
$$

(3)

6
\[ T^\mu = \frac{1}{2} (1 + \not{v}) \left[ D^\mu_2 \gamma_\nu - \sqrt{\frac{3}{2}} \tilde{D}_1 \gamma_5 \left( g^{\mu\nu} - \frac{1}{3} \gamma^\nu (\gamma^\mu - v^\mu) \right) \right], \tag{4} \]

where \( v \) is the meson four-velocity and \( a \) is a light quark flavour index. Light meson fields are included in Lagrangian (1) through \( \mathcal{A}^\mu = \frac{1}{2} (\xi^\dagger \partial^\mu \xi - \xi \partial^\mu \xi^\dagger) \), where \( \xi = \exp(\frac{G}{f}) \) and

\[
\tilde{\pi} = \begin{pmatrix} \frac{\eta}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{-\eta}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \frac{-\eta}{\sqrt{2}} - \frac{\eta}{\sqrt{6}} & \eta \end{pmatrix}. \tag{5} \]

In our discussion we consider the term of Lagrangian (1) describing the coupling of a state of the \( \frac{1}{2}^+ \) doublet with one of the \( \frac{1}{2}^- \) doublet and a light pseudoscalar meson. Such interaction is characterized by the coupling constant \( h \), for which we use a value calculated in the framework of QCD sum rules: \( |h| = 0.6 \pm 0.2 \) \[20\].

Due to parity and angular momentum conservation and consistently with the experimental masses, the only two-body strong decays allowed for the non strange 0+ and 1+ states are those in \( D\pi \) and \( D^*\pi \), respectively. Considering the average value of the masses measured by Belle and FOCUS, we obtain: \( \Gamma(D_0^0 \to D^+\pi^-) = 260 \pm 54 \text{ MeV} \) and \( \Gamma(D_1' \to D^{*+}\pi^-) = 160 \pm 25 \text{ MeV} \), where the errors reflect the uncertainties of the computational scheme. Taking into account also decays in \( D^0\pi^0 \) and \( D^{*0}\pi^0 \) we obtain \( \Gamma(D_0^0) \sim \frac{2}{3} \Gamma(D_0^{*0} \to D^+\pi^-) = 390 \pm 80 \text{ MeV} \) and \( \Gamma(D_1') \sim \frac{2}{3} \Gamma(D_1' \to D^{*+}\pi^-) = 240 \pm 40 \text{ MeV} \).

For \( c\bar{s} \) states the derivation of the width is less direct than in the non strange case, due to the isospin violation occurring in \( D_{s,d} \to D_s^{(s)}\pi^0 \) decays. These decays can be interpreted through a process in two steps: an isospin-conserving decay with a virtual \( \eta \) in the final state and a \( \pi^0 - \eta \) mixing due to the difference in mass between u and d quarks. In fact the mass term in the low energy Lagrangian describing \( \pi \), K and \( \eta \) mesons, \( \mathcal{L} = \frac{\bar{u}d}{4} \text{Tr} \left[ \xi m_d + \xi^\dagger m_u \xi^\dagger \right] \), gives rise to the following matrix element, vanishing in the limit \( m_u = m_d \):

\[
\langle \pi^0|\eta \rangle = \frac{\bar{u} m_d - m_u}{2 \sqrt{3}}. \tag{6} \]

The resulting expression for the \( D_{s0}^* \to D_s\pi^0 \) width is

\[
\Gamma(D_{s0}^* \to D_s\pi^0) = \frac{1}{16\pi} \frac{\hbar^2 M_{D_s}}{f^2 M_{D_{s0}}} \left( \frac{m_{\pi^0}^2}{m_{\pi^0}^2 + |\eta|^2} \right) \left| \eta \right| \left( \frac{m_u - m_d}{m_u + m_d - m_s} \right)^2, \tag{7} \]

whereas the \( D_{s1}' \to D_s^{*0}\pi^0 \) width is expressed by a relation similar to (7), the only difference consisting in a factor \( \frac{1}{3} \left( 2 + \frac{(M_{D_{s1}}^2 + M_{D_{s1}}^2 - m_{\pi^0}^2)^2}{4 M_{D_{s1}}^2 M_{D_{s1}}^2} \right) \). Using the factor \( \frac{m_u + m_d}{m_s} \approx \frac{1}{43.7} \) \[21\], the results \( \Gamma(D_{s0}^* \to D_s\pi^0) = 7 \pm 1 \text{ KeV} \) and \( \Gamma(D_{s1}' \to D_s^{*0}\pi^0) = 7 \pm 1 \text{ KeV} \) can be obtained, so that hadronic widths result of the typical size of radiative widths.
5 Mixing between \( (1^+)_\frac{1}{2} \) and \( (1^+)_\frac{3}{2} \) states

In computing strong widths for the axial states of \( \epsilon \pi \) and \( \epsilon \pi \) systems we have implicitly assumed that \( (1^+)_\frac{1}{2} \) and \( (1^+)_\frac{3}{2} \) states do not mix. Due to the finite mass of charm it is instead possible that physical states are the result of a mixing through an angle \( \theta \) of HQET states. We could have an evidence of such a mixing if using for the coupling constant \( \frac{\alpha'}{\Lambda^2} \) appearing in Lagrangian (1) the value we deduce from the experimental width of the \( (2^+)_\frac{3}{2} \) state we compute a width for the \( (1^+)_\frac{1}{2} \) state inconsistent with the experimental measurements.

Table 4: Masses and widths for \( s_\pi^P = \frac{3}{2} \) \( \epsilon \pi \) states recently measured by Belle and FOCUS, together the corresponding quantities reported on Particle Data Group.

|       | Belle [1] | FOCUS [2] | PDG [22] |
|-------|-----------|-----------|-----------|
| \( D^0_1 \) | Mass (MeV) | 2421 ± 1.5 ± 0.8 | - | 2422.2 ± 1.8 |
|       | Width (MeV) | 23.7 ± 2.7 ± 0.2 ± 4.0 | - | 18.9 ± 4.0 |
| \( D^0_2 \) | Mass (MeV) | 2462 ± 2.1 ± 0.5 ± 3.3 | 2464.5 ± 1.1 ± 1.9 | 2458.9 ± 2.0 |
|       | Width (MeV) | 45.6 ± 4.4 ± 6.5 ± 1.6 | 38.7 ± 5.3 ± 2.9 | 23 ± 5 |

In fitting \( D^{**} \) resonances Belle and FOCUS have measured masses and widths for the narrow \( \frac{3}{2}^+ \) states different from those reported on PDG, as it is shown in Table 4. The previous experimental measurements could be affected by systematical errors due to the neglect of the broad resonances. The experimental value for \( \frac{\alpha'}{\Lambda^2} \) deduced using these new measurements is \( (0.72 ± 0.06) \times 10^{-3} \). Using this experimental value we obtain a width \( \Gamma(D^0_1) = (17 ± 6) \) MeV, which is consistent with Belle measurement. So we conclude that, using recent data, there is no evidence of a large mixing\(^1\).

6 Radiative decays

The amplitude of radiative decays of mesons containing a single heavy quark can be determined through a method based on the use of heavy quark symmetries together with the vector meson dominance (VMD) ansatz.

Computing the coupling of the photon to the heavy quark part of the e.m. current in the heavy quark limit one obtains that the matrix element \( \langle D^s(p', \epsilon) | p \gamma_\mu c | D^s_0(p + q) \rangle \) is proportional to the inverse heavy quark mass, so that this contribution can be neglected. Invoking the VMD ansatz the coupling of the photon with the light quark can be expressed through an intermediate light vector meson, for example \( \phi(1020) \) in the case of heavy mesons with strangeness:

\[
\langle D^s(p, \epsilon) | D^s_0(p + q) \rangle \simeq ee_s \sum_\lambda \left\langle D^s(p, \epsilon) \phi(q, \eta^{(\lambda)}) | D^s_0(p + q) \right\rangle \frac{i}{q^2 - m_\phi^2} \cdot \langle 0 | \bar{\psi} \gamma_\mu s | \phi(q, \eta^{(\lambda)}) \rangle \bar{c}_\mu .
\]  

The interaction of a light vector meson with two heavy mesons can be described by means of a

\(^1\)In ref. [1] a mixing angle of \( \theta \simeq -0.10 \) rad is estimated.
Lagrangian derived in [23] through the hidden gauge symmetry method:

\[ \mathcal{L}' = i\mathcal{M}Tr\{\mathcal{S}aH_b\sigma^{\lambda\nu}V_{\lambda\nu}(\rho)_{ba}\} + h.c. \quad (9) \]

where \( V_{\lambda\nu}(\rho) = \partial_\lambda \rho_\nu - \partial_\nu \rho_\lambda + [\rho_\lambda, \rho_\nu] \) and \( \rho_\lambda = i\frac{g_{\lambda\nu}}{2}\tilde{\rho}_{\lambda\nu} \), \( \tilde{\rho}_{\lambda\nu} \) being a 3×3 matrix analogue to \( \tilde{\pi} \) defined in (5) and \( g_\nu \) being fixed to \( g_\nu = 5.8 \) in [24]. Using for \( \tilde{\mu} \) the value deduced through the analysis of the \( D \to K^{*} \) semileptonic transitions in [25], we obtain for states with strangeness:

\[ \Gamma (D_{s0}^{*} \to D_{s}^{*}\gamma) \approx 1 \text{ KeV}, \quad \Gamma (D_{s1}^{*} \to D_{s}\gamma) \approx 3.3 \text{ KeV} \text{ and } \Gamma (D_{s1}^{*} \to D_{s}^{*}\gamma) \approx 1.5 \text{ KeV}. \]

Our results for ratios between strong and radiative decay rates for these narrow states are shown in Table 5 together the corresponding data of Belle, BaBar and CLEO Collaborations. The most meaningful comparison is that for the only observed radiative decay: our result for \( \frac{\Gamma(D_{s1}^{*} \to D_{s}\gamma)}{\Gamma(D_{s1}^{*} \to D_{s}^{*}\pi^0)} \) is consistent with both Belle and BaBar measurements.

Table 5: Decay fractions for \( \frac{1}{2}^+ \) states with strangeness. The values labeled by (*) are those obtained from B decays data reported in [9], [10]. The other ones result from Belle [4] and CLEO [5] continuum analysis.

| \( \Gamma(D_{s0}^{*} \to D_{s}^{*}\gamma) \) | Belle | BaBar | CLEO | prediction |
|-----------------------------------------|-------|-------|------|------------|
| \( \Gamma(D_{s0}^{*} \to D_{s}\pi^0) \) | (**) 0.29 ± 0.26 (< 0.9) | —     | < 0.059 | 0.1        |
| \( \Gamma(D_{s1}^{*} \to D_{s}\gamma) \) | (**) 0.38 ± 0.11 ± 0.04 | 0.55 ± 0.13 ± 0.08 | (**) 0.44 ± 0.17 | < 0.49 | 0.5 |
| \( \Gamma(D_{s1}^{*} \to D_{s}\pi^0) \) | (**) 0.15 ± 0.11 (< 0.4) | —     | < 0.16 | 0.2        |
| \( \Gamma(D_{s1}^{*} \to D_{s}\pi^0) \) | (**) 0.40 ± 0.28 (< 1.1) | —     | —     | 0.4        |

Using the same method, we have obtained for the radiative decays of \( c\bar{c} \) and \( c\bar{d} \) states the following rates:

\( \Gamma (D_{0}^{*0} \to D^{*0}\gamma) = 26 \pm 4 \text{ KeV}, \quad \Gamma (D_{0}^{*+} \to D^{*+}\gamma) = 7 \pm 1 \text{ KeV}, \quad \Gamma (D_{1}^{*+} \to D^{*+}\gamma) = 13 \pm 3 \text{ KeV}, \quad \Gamma (D_{1}^{*0} \to D^{0}\gamma) = 50 \pm 10 \text{ KeV}, \quad \Gamma (D_{1}^{*0} \to D^{*0}\gamma) \approx 7 \text{ KeV}, \quad \Gamma (D_{1}^{*0} \to D^{*0}\gamma) \approx 7 \text{ KeV}. \)

7 Predictions for beauty mesons belonging to \( \frac{1}{2}^+ \) doublet

The method applied for \( c\bar{c} \) states of the \( \frac{1}{2}^+ \) doublet can be also used for the analogue \( b\bar{b} \) states. Since there is no experimental evidence for the latter, at first we have to estimate their masses.

In the HQET framework the masses of heavy mesons belonging to the \( \frac{1}{2}^- \) doublet are expressed through the following relation:

\[ m_M = m_Q + \overline{\Lambda} + \frac{\Delta m_M^2}{2m_Q} + ..., \quad (10) \]

where \( M=\text{P}, \text{V} \) (pseudoscalar, vector). In eq. (10) the parameter \( \overline{\Lambda} \) is independent of heavy quark flavour and spin, while the correction \( \frac{\Delta m_M^2}{2m_Q} \) can be parameterized through the relation \( \Delta m_M^2 = ... \)
\[-\lambda_1 + d_M \lambda_2, \text{ where } \lambda_1 \text{ and } \lambda_2 \text{ are related, respectively, to the matrix elements of the kinetic and chromomagnetic operators appearing as } O \left( \frac{1}{m_Q} \right) \text{ corrections to the HQET Lagrangian. Since } d_P = -3 \text{ and } d_V = 1, \text{ one can consider the spin averaged mass } \bar{m} = \frac{m_P + 3m_V}{4} = m_Q + \overline{\Lambda} - \frac{\lambda_1}{2m_Q}, \text{ and the analogue expression } \bar{m}^* \text{ for the } \frac{1}{2}^+ \text{ doublet. Disregarding the } \frac{\lambda_1 - \lambda_2}{2m_Q} \text{ term in both charm and beauty cases, we obtain the relation}

\[\bar{m}^*_b[b] = \bar{m}[b] + \bar{m}^*_c[c] - \bar{m}[c], \tag{11}\]

by means of which we predict for \(\frac{1}{2}^+\) beauty mesons masses the values shown in Table 6. The \(B_{s0}^*\) and \(B_{s1}'\) masses are predicted to be below BK and B*K thresholds, respectively, and so these states are expected to be detected as narrow resonances in the \(B_s\pi^0\) and \(B_s'^\pi^0\) systems, analogously to the charm case. Using these mass predictions we have computed strong and radiative decay rates, obtaining total widths reported in Table 6 and decay fractions shown in Table 7 [28]. Other predictions concerning the masses of \(\frac{1}{2}^+ \bar{b}q\) mesons are collected in [28], see also [29].

**Table 6: Masses and widths predicted for \(\bar{b}q\) states belonging to \(\frac{1}{2}^+\) doublet.**

| meson       | mass (MeV) | width (MeV) |
|-------------|------------|-------------|
| \(B_{s0}^0\) | 5710       | 330 ± 24    |
| \(B_{s0}^*\) | 5721       | (10.5 ± 0.5) \times 10^{-3} |
| \(B_1^0\)   | 5744       | 204 ± 14    |
| \(B_{s1}'\) | 5762       | (11 ± 0.5) \times 10^{-3} |

**Table 7: Decay fractions predicted for \(\bar{b}s\) states belonging to \(\frac{1}{2}^+\) doublet.**

| prediction | prediction |
|------------|------------|
| \(\Gamma(B_{s0}^* \rightarrow B_s^*\gamma)\) | 0.4 |
| \(\Gamma(B_{s0}^* \rightarrow B_s\pi^0)\) | 0.3 |
| \(\Gamma(B_{s1}' \rightarrow B_s\gamma)\) | 0.3 |
| \(\Gamma(B_{s1}' \rightarrow B_s\pi^0)\) | 0.3 |

**8 Conclusions**

To test the interpretation of the recently observed resonances as \(c\bar{q}\) states of the \(\frac{1}{2}^+\) doublet we have computed their strong and radiative decay rates in this hypothesis, using experimental masses. For non strange states we have obtained widths of several hundreds MeV, consistently with the measurements, whereas for states with strangeness strong decay rates are obtained of the same order of the radiative ones, so that their total widths result to be very narrow, in agreement with the experimental observations. For the ratios \(\frac{\Gamma(D_{s1}' \rightarrow D_s\gamma)}{\Gamma(D_{s1}' \rightarrow D_s\pi^0)}\) our result is consistent with both measurements performed by Belle. Ratios of the same order are obtained for the radiative decays \(D_{s0} \rightarrow D_s^*\gamma\) and \(D_{s1} \rightarrow D_s^*\gamma\), though such processes have not been observed yet. Only
upper limits at 90\% C. L. are available, with which our results are in substantial agreement, as shown in Table 5. So we conclude that the experimental observations are compatible with the interpretation of these resonances as $c\bar{q}$ states of the $1/2^+$ doublet, although the question concerning the low masses of the states with strangeness remains an open issue. This interpretation, also proposed in [26]-[27], could be corroborated by a future observation of the other expected radiative decays.

Finally, we have predicted masses and widths for $b\bar{q}$ states of the $1/2^+$ doublet. For $b\bar{q}$ states, we obtain a scenario similar to the corresponding one in the charm case, so that we expect that $B_{s0}^*$ and $B_{s1}^*$ can be observed as narrow resonances in the $B_s\pi^0$ and $B_s^*\pi^0$ systems. Too heavy to be produced at B-factories, such resonances could be discovered in hadronic experiments like CDF, or through a LEP data reanalysis.

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