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On the mass differences between the scalar and pseudoscalar heavy-light mesons

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Abstract

We discuss the recent experimental observation which suggested that the mass difference between the scalar and pseudoscalar heavy-light mesons is larger for the non-strange states than for the strange ones. After computing the chiral corrections in the heavy quark limit we show that, contrary to experiment, the mass difference in the non-strange case should be smaller.

1. Conflict between theory and experiment

High statistics B-factory experiments at BaBar and Belle, besides providing the substantial information about the CP-violation in the processes involving B-mesons, also allowed for a precision measurement of the D-meson spectrum. Together with CLEO and FOCUS, all four experiments reported the presence of the narrow scalar ($J^P = 0^+$) and axial ($J^P = 1^+$) states [1], the average of which is found to be

$$m_{D_{s0}^*}^{(0^+)} = 2317.0(4)\ \text{MeV},$$

$$m_{D_{s1}'}^{(1^+)} = 2458.2(1.0)\ \text{MeV}. \qquad (1)$$

These results were somewhat surprising because both the scalar and axial states are below the threshold of their dominant—Zweig allowed—modes, namely $m_{D_{s0}^*} < m_D + m_K$ and $m_{D_{1s}'} < m_{D^*} + m_K$. Therefore the newly observed states are very narrow, contrary to what has been predicted by many potential quark models [2].[2] This motivated many authors to either generalise the quark model potentials as to accommodate the narrowness of the mentioned states [4], employ the unitarised meson model to the charmed scalar states [5], or to revive the old ideas about the molecu-

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[2] Note however that such a low scalar state mass was anticipated in the model calculation of Ref. [3].

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lar structure of these excitations [6]. Before attributing something exotic to the states (1), one should carefully check if the minimal "quark–antiquark" picture, which has been so successful in the history of hadron spectroscopy, indeed fails. Such a test cannot be made by insisting on the accuracy of the quark models at a percent level because of the questionable contact of any specific quark model parameter with QCD. A reliable test of compatibility between the "quark–antiquark" picture and the observed hadronic spectra could be made by means of the fully unquenched high statistics lattice studies, which are unfortunately not yet available. The two partially quenched lattice studies, that appeared after the announcement of the experimental numbers (1), reached two different conclusions: while Ref. [7] suggests that the new states are unlikely to be the scalar and axial quark–antiquark mesons, in Ref. [8] the difference between the scalar and pseudoscalar charm-strange mesons is shown to be consistent with the experimentally measured ones.[3]

When cataloging the heavy-light mesons it is customary to use the heavy quark spin symmetry according to which the total angular momentum of the light degrees of freedom (j_ℓ^P) is a good quantum number so that the heavy-light mesons come in doublets of a common j_ℓ^P, e.g.,

$$\underbrace{\big[D_{(s)}(0^-), D^*_{(s)}(1^-)\big]}_{j_\ell^P=\frac{1}{2}^-(L=0)}, \qquad \underbrace{\big[D^*_{0(s)}(0^+), D'_{1(s)}(1^+)\big]}_{j_\ell^P=\frac{1}{2}^+(L=1)}, \\ \underbrace{\big[D_{1(s)}(1^+), D^*_{2(s)}(2^+)\big]}_{j_\ell^P=\frac{3}{2}^+(L=1)}, \quad \ldots \tag{2}$$

where the index "s" helps distinguishing the strange from non-strange heavy-light mesons.

After comparing to the well known lowest states (belonging to $j_\ell^P = \frac{1}{2}^-$) [10], we see that the splittings

$$\Delta m_s(0) \equiv m_{D^*_{0s}} - m_{D_s} = 348.4(9)\ \text{MeV}, \\ \Delta m_s(1) \equiv m_{D'_{1s}} - m_{D^*_s} = 345.9(1.2)\ \text{MeV}, \tag{3}$$

are equal. In other words the hyperfine splitting in the first orbitally excited doublet is indistinguishable from the one in the ground state doublet. Although various quark models give different numerical estimates for $\Delta m_s(0)$, almost all of them share a common feature, namely this orbital splitting remains almost unchanged after replacing the light s- by u- or d-quark. The surprise (now for real) actually came from experiment when Belle reported [11]

$$\Delta m_u(0) \equiv m_{D^*_0} - m_D = 444(36)\ \text{MeV}, \\ \Delta m_u(1) \equiv m_{D'_1} - m_{D^*} = 420(36)\ \text{MeV}, \tag{4}$$

clearly larger than the ones with the strange light quark (3), even though the error bars in the non-strange results are much larger which reflects the experimental difficulty in identifying the broad states. The confirmation of this phenomenon came recently by FOCUS [12], namely,

$$m_{D^*_0} = 2407(21)(35)\ \text{MeV} \\ \Longrightarrow \Delta m_u(0) = 538(41)\ \text{MeV}. \tag{5}$$

This truly surprising phenomenon requires an explanation. Since, to a very good approximation, $\Delta m_{u,s}(0) = \Delta m_{u,s}(1)$, we shall concentrate on $\Delta m_{u,s}(0)$ and argue that the experimentally established inequality

$$\big[\Delta m_u(0) - \Delta m_s(0)\big]^{\text{exp}} > 0, \tag{6}$$

is in conflict with theory if the phenomenon is examined by means of chiral perturbation theory (ChPT). A similar conclusion has been reached by the model calculations of Ref. [13].

2. Chiral Lagrangian for doublets of heavy-light mesons

The lagrangian that is necessary for studying the mass difference between the $\frac{1}{2}^+$ and $\frac{1}{2}^-$ heavy-light states is [14]

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\frac{1}{2}^-} + \mathcal{L}_{\frac{1}{2}^+} + \mathcal{L}_{\text{mix}} + \mathcal{L}_{\text{ct}}, \\
\mathcal{L}_{\frac{1}{2}^-} &= i\,\text{Tr}\big[H_b v\cdot D_{ba}\bar{H}_a\big] + g\,\text{Tr}\big[H_b\gamma_\mu\gamma_5 \mathbf{A}^\mu_{ba}\bar{H}_a\big], \\
\mathcal{L}_{\frac{1}{2}^+} &= -\text{Tr}\big[S_b(iv\cdot D_{ba} + \Delta_S)\bar{S}_a\big] \\
&\quad + \tilde{g}\,\text{Tr}\big[S_b\gamma_\mu\gamma_5\mathbf{A}^\mu_{ba}\bar{S}_a\big], \\
\mathcal{L}_{\text{mix}} &= h\,\text{Tr}\big[S_b\gamma_\mu\gamma_5\mathbf{A}^\mu_{ba}\bar{H}_a\big] + \text{h.c.}, \\
\mathcal{L}_{\text{ct}} &= \text{Tr}\big[\big(\lambda\bar{H}_a H_b - \tilde{\lambda}\bar{S}_a S_b\big)\big(\xi\mathcal{M}\xi + \xi^\dagger\mathcal{M}\xi^\dagger\big)_{ba}\big] \\
&\quad + \text{Tr}\big[\big(\lambda'\bar{H}_a H_a - \tilde{\lambda}'\bar{S}_a S_a\big) \\
&\quad \times \big(\xi\mathcal{M}\xi + \xi^\dagger\mathcal{M}\xi^\dagger\big)_{bb}\big],
\end{aligned} \tag{7}$$

[3] Compatibility with observation was also claimed on the basis of results obtained by using the QCD sum rules [9].

where the fields of pseudoscalar (P), vector (P^*_μ), scalar (P_0) and axial ($P^*_{1\,\mu}$) mesons are organised in superfields

$$
\begin{aligned}
H_a(v) &= \frac{1+\not v}{2}\big[P^{*\,a}_\mu(v)\gamma_\mu - P^a(v)\gamma_5\big],\\
\bar H_a(v) &= \gamma_0 H_a^\dagger(v)\gamma_0,\\
S_a(v) &= \frac{1+\not v}{2}\big[P^{*\,a}_{1\,\mu}(v)\gamma_\mu\gamma_5 - P_0^a(v)\big],\\
\bar S_a(v) &= \gamma_0 S_a^\dagger(v)\gamma_0,
\end{aligned}
\tag{8}
$$

with "a" and "b" labelling the light quark flavour. In addition

$$
\begin{aligned}
D^\mu_{ba}H_b &= \partial^\mu H_a - H_b \mathbf{V}^\mu_{ba}\\
&= \partial^\mu H_a - H_b\frac{1}{2}\big[\xi^\dagger\partial_\mu\xi + \xi\partial_\mu\xi^\dagger\big]_{ba},\\
\mathbf{A}^{ab}_\mu &= \frac{i}{2}\big[\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger\big]_{ab},\\
\xi &= \sqrt{\Sigma},\quad \Sigma = \exp\left(2i\frac{\phi}{f}\right),
\end{aligned}
\tag{9}
$$

with $f \approx 130$ MeV, $\mathcal{M} = \mathrm{diag}(m_u, m_d, m_s)$, and ϕ the usual matrix of pseudo-Goldstone bosons,

$$
\phi = \begin{pmatrix}
\frac{1}{\sqrt2}\pi^0 + \frac{1}{\sqrt6}\eta & \pi^+ & K^+\\
\pi^- & -\frac{1}{\sqrt2}\pi^0 + \frac{1}{\sqrt6}\eta & K^0\\
K^- & \bar K^0 & -\frac{2}{\sqrt6}\eta
\end{pmatrix}.
\tag{10}
$$

g and $\tilde g$ are the couplings of the Goldstone boson to the pair of heavy-light mesons with $j_\ell^P = \frac12^-$ and $\frac12^+$, respectively.[4] h, instead, is the coupling of a Goldstone boson and the heavy-light mesons belonging to different heavy quark spin doublets, namely one meson is $\frac12^-$ and the other $\frac12^+$ state. The meson masses are $m_{H_{\frac12^\pm}} = m_Q + \mathcal{E}_{\frac12^\pm}$, whereas the difference between the binding energies in the first orbital excitation and in the lowest lying heavy meson states is denoted by $\Delta_S = \mathcal{E}_{\frac12^+} - \mathcal{E}_{\frac12^-}$.

[4] The coupling g is proportional to the commonly used coupling $g_{D^*D\pi}$, whereas $\tilde g$ is proportional to $g_{D_0^*D_1'\pi}$.

3. Chiral correction to the mass of heavy-light mesons

Since we work in the heavy quark limit, the heavy-light meson propagator is a function of $v\cdot k$ only. $k_\mu = p_{P\mu} - m_Q v_\mu$, is the momentum of the light degrees of freedom in the heavy-light meson. The chiral dressing of the $\frac12^-$-meson propagator,

$$
G^q_{\frac12^-}(v\cdot k) = \frac{i}{2v\cdot k} + \frac{i}{2v\cdot k}\big(-i\Sigma_q(v\cdot k)\big)\frac{i}{2v\cdot k} + \cdots,
\tag{11}
$$

generates a shift to its binding energy, $\mathcal{E}_{\frac12^-} \to \mathcal{E}_{\frac12^-} + \delta\mathcal{E}^q_{\frac12^-}$, where

$$
\delta\mathcal{E}^q_{\frac12^-} = \frac12 \lim_{v\cdot k\to 0}\Sigma_q(v\cdot k).
\tag{12}
$$

Similarly,

$$
\begin{aligned}
G^q_{\frac12^+}(v\cdot k)
&= \frac{i}{2(v\cdot k - \Delta_S)} + \frac{i}{2(v\cdot k - \Delta_S)}\\
&\quad\times\big(-i\tilde\Sigma_q(v\cdot k)\big)\frac{i}{2(v\cdot k-\Delta_S)} + \cdots
\end{aligned}
\tag{13}
$$

leads to

$$
\delta\mathcal{E}^q_{\frac12^+} = \frac12 \lim_{v\cdot k\to 0}\tilde\Sigma_q(v\cdot k).
\tag{14}
$$

Therefore the mass splitting between $\frac12^+$ and $\frac12^-$ states in the heavy quark limit is

$$
\Delta m_q(0) = \Delta_S + \delta\mathcal{E}^q_{\frac12^+} - \delta\mathcal{E}^q_{\frac12^-},
\tag{15}
$$

where the light valence quark in the heavy-light meson, $q \in \{u/d, s\}$. We will work in the isospin limit, $m_u = m_d = m_{u/d}$. We focus onto the scalar meson and compute the chiral loop corrections illustrated in Fig. 1.

$$
\begin{aligned}
-i\tilde\Sigma^{(a)}_q(v\cdot k)
&= \sum_{i=1}^{8}\sum_{a=1}^{3}\int\frac{d^4p}{(2\pi)^4}\frac{-2\tilde g p^\alpha}{f}\big(t^{i\dagger}\big)_{qa}\\
&\quad\times\frac{-i(g_{\alpha\beta} - v_\alpha v_\beta)}{2v\cdot(k+p)}\frac{2\tilde g p^\beta}{f}\big(t^i\big)_{aq}\frac{i}{p^2 - m_i^2}.
\end{aligned}
\tag{16}
$$

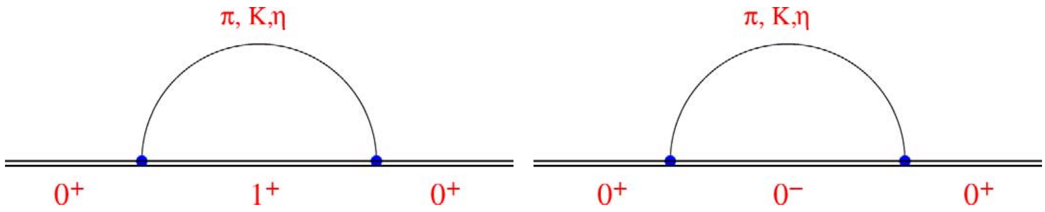

Fig. 1. Graphs contributing to the chiral shift in the binding energy of the scalar meson $J^P = 0^+$. By flipping all the parity signs, one gets the graphs relevant to the case of pseudoscalar meson also discussed in the text.

This integral is standard and the result is expressed in terms of functions $J_{1,2}$ (explicit expressions can be found in, for example, Appendix A of Ref. [15]) leading to

$$-i\tilde{\Sigma}_q^{(a)}(v\cdot k) = \sum_{i=1}^{8} \frac{-2\tilde{g}^2}{f^2}\left(t^i t^i\right)_{qq} \frac{3i}{(4\pi)^2}(v\cdot k) J_1(m_i, -v\cdot k)$$

$$\Longrightarrow \lim_{v\cdot k\to 0} \tilde{\Sigma}_q^{(a)}(v\cdot k) = -\frac{6\tilde{g}^2}{(4\pi f)^2}\sum_{i=1}^{8}\left(t^i t^i\right)_{qq}\frac{2\pi}{3}m_i^3. \tag{17}$$

In a completely analogous way, after exchanging "+" ↔ "−" in the graph (a), we have

$$\lim_{v\cdot k\to 0} \Sigma_q^{(a)}(v\cdot k) = -\frac{6g^2}{(4\pi f)^2}\sum_{i=1}^{8}\left(t^i t^i\right)_{qq}\frac{2\pi}{3}m_i^3. \tag{18}$$

As for the diagram (b) we obtain

$$\begin{aligned}
-i\tilde{\Sigma}_q^{(b)}(v\cdot k) &= \sum_{i=1}^{8}\sum_{a=1}^{3}\int \frac{d^4p}{(2\pi)^4}\frac{-2hv_\alpha}{f}\left(t^{i\dagger}\right)_{qa} \\
&\quad\times \frac{ip^\alpha p^\beta}{2[v\cdot(k+p)-(-\Delta_S)]}\frac{2hv_\beta}{f}\left(t^i\right)_{aq}\frac{i}{p^2-m_i^2} \\
&= -\frac{2ih^2}{(4\pi f)^2}\sum_{i=1}^{8}\left(t^i t^i\right)_{qq}(-\Delta_S - v\cdot k) \\
&\quad\times\left[J_1(m_i, -\Delta_S - v\cdot k) + J_2(m_i, -\Delta_S - v\cdot k)\right],
\end{aligned} \tag{19}$$

and therefore

$$\begin{aligned}
\lim_{v\cdot k\to 0}\tilde{\Sigma}_q^{(b)}(v\cdot k) &= -\frac{2h^2\Delta_S}{(4\pi f)^2}\sum_{i=1}^{8}\left(t^i t^i\right)_{qq} \\
&\quad\times\left[J_1(m_i, -\Delta_S) + J_2(m_i, -\Delta_S)\right].
\end{aligned} \tag{20}$$

Similarly,

$$\begin{aligned}
\lim_{v\cdot k\to 0}\Sigma_q^{(b)}(v\cdot k) &= \frac{2h^2\Delta_S}{(4\pi f)^2}\sum_{i=1}^{8}\left(t^i t^i\right)_{qq} \\
&\quad\times\left[J_1(m_i, \Delta_S) + J_2(m_i, \Delta_S)\right].
\end{aligned} \tag{21}$$

Notice that compared to Eq. (20) the sign in front of Δ_S in the argument of the functions $J_{1,2}$ is now changed. This reflects the fact that the intermediate heavy-light meson, with respect to the mass of the meson in the external leg, is now heavier.

After collecting the above expressions into Eq. (15), we arrive at

$$\begin{aligned}
\Delta m_q(0) = \Delta_S\Bigg(1 &- \frac{h^2}{(4\pi f)^2}\left(t^i t^i\right)_{qq} \\
&\times\sum_{z=\pm}\left[J_1(m_i, z\Delta_S) + J_2(m_i, z\Delta_S)\right]\Bigg) \\
&+ \frac{g^2-\tilde{g}^2}{8\pi f^2}\left(t^i t^i\right)_{qq} m_i^3 + 2(\tilde{\lambda}-\lambda)m_q \\
&+ 2\left(\tilde{\lambda}'-\lambda'\right)(m_u+m_d+m_s),
\end{aligned} \tag{22}$$

where in the last line we also included the counterterms, thus completing the NLO chiral corrections to the mass splitting we consider. The integrals $J_{1,2}$ also carry an implicit dependence on the scale μ which cancels against the one in $\tilde{\lambda}' - \lambda'$. Finally, in evaluating the integrals $J_{1,2}$, we set $\bar{\Delta} = 0$ (see Eq. (44) of Ref. [15]).

Note that in our loop calculations we include the light pseudogoldstone bosons only. The inclusion of light resonances, such as ρ, K^*, ϕ, would involve higher orders in chiral expansion which is beyond the scope of the approach adopted in this Letter [16].

4. Chiral enhancement or suppression?

To examine whether or not the apparent chiral enhancement observed experimentally can be explained by the approach adopted in this Letter we need to consider

$$\begin{aligned}
&\Delta m_{u/d}(0) - \Delta m_s(0) \\
&\quad = \frac{h^2 \Delta_S}{(4\pi f)^2} \sum_{z=\pm} \biggl[J_1(m_K, z\Delta_S) + \frac{1}{2} J_1(m_\eta, z\Delta_S) \\
&\qquad - \frac{3}{2} J_1(m_\pi, z\Delta_S) + J_2(m_K, z\Delta_S) \\
&\qquad + \frac{1}{2} J_2(m_\eta, z\Delta_S) - \frac{3}{2} J_2(m_\pi, z\Delta_S) \biggr] \\
&\qquad - \frac{g^2 - \tilde{g}^2}{16\pi f^2} \left(m_\eta^3 + 2m_K^3 - 3m_\pi^3 \right) \\
&\qquad - 2(\lambda - \tilde{\lambda})(m_{u/d} - m_s).
\end{aligned} \tag{23}$$

By using the Gell-Mann formulae,

$$m_\pi^2 = 2B_0 m_s r, \qquad m_K^2 = 2B_0 m_s \frac{r+1}{2},$$
$$m_\eta^2 = 2B_0 m_s \frac{r+2}{3}, \tag{24}$$

where $r = m_{u/d}/m_s$ and $2B_0 m_s = 2m_K^2 - m_\pi^2 = 0.468\ \text{GeV}^2$, we can simply plot the Eq. (23) against the variation of r, the light quark mass with respect to the strange quark which is kept fixed to its physical value. Before doing so we discuss our choice of values for the couplings h, g and $\tilde{g}$, and for the low energy constant $\lambda - \tilde{\lambda}$:

- g-coupling has been determined experimentally from the width of the charged D^*-meson, $g = 0.61(1)(6)$ [17];[5]
- There is no experimental determination of the axial coupling in the orbitally excited doublet, $\tilde{g}$. While the non-relativistic quark model predicts $|\tilde{g}/g| = 1/3$, a relativistic model which correctly predicted g before it was measured [19], one gets $\tilde{g} = 0.03$. The QCD sum rule based estimates are $\tilde{g} = 0.10(2)$ [20]. To cover the whole range of values we will take $\tilde{g} = 0.2(2)$;
- The experimental situation with h, the pionic coupling between mesons belonging to different doublets, is less clear. If we take the mass and width of the scalar meson as measured by Belle [11], we get $h = 0.78(9)(8)$, while those measured by FOCUS [12] give $h = 0.56(8)(6)$, in a very good agreement with the QCD sum rule estimates $h = 0.60(13)$ [20]. From the recent lattice computation of the width of the scalar heavy-light state [21], we deduce $h = 0.62(6)(4)$, where we used the scalar meson mass measured by Belle [$m_{D_0^*} = 2308(36)$ MeV], which is more reliable than the one measured by FOCUS in that Belle properly separate 0^+ and 1^+ signals.[6] The model of Ref. [19] predicts $h \simeq 0.54$. To take the full spread of the mentioned values we will use $h = 0.6(2)$.
- In the recent unquenched lattice study [22], it has been shown that the splitting that we discuss in this Letter changes very weakly when the light quark is varied between $r = 0.65$ and $r \simeq 1$. We will then fix the value of K in $2(\lambda - \tilde{\lambda})(m_{u/d} - m_s) \to K(m_\pi^2 - m_K^2)$, by imposing the limit that Eq. (23) allows for a variation smaller than or equal to -50 MeV, for $r \in (0.65, 1]$. Limiting values are $K(1\ \text{GeV}) \simeq 0.7\ \text{GeV}^{-1}$, for the variation to -50 MeV, and $K(1\ \text{GeV}) \simeq 1.3\ \text{GeV}^{-1}$, for no variation at all.[7]

In Fig. 2 we plot the result of Eq. (23) by using the central values for the couplings listed above. In addition we take $\Delta_S = 0.35$ GeV. We see that when the pion becomes lighter than Δ_S, the self energies develop the imaginary part, which reflects the fact that the real pion can be emitted via $P_0^* \to P\pi$. Most importantly, we see that the real part remains always neg-

[5] A short review of lattice and QCD sum rule estimates of this quantity can be found in Ref. [18].

[6] We thank the referee for drawing our attention to this point.

[7] These values are obtained by choosing $\mu = 1$ GeV. Had we chosen any other μ, the corresponding $K(\mu)$ would be different but the resulting $\Delta m_{u/d}(0) - \Delta m_s(0)$ would obviously remain the same.

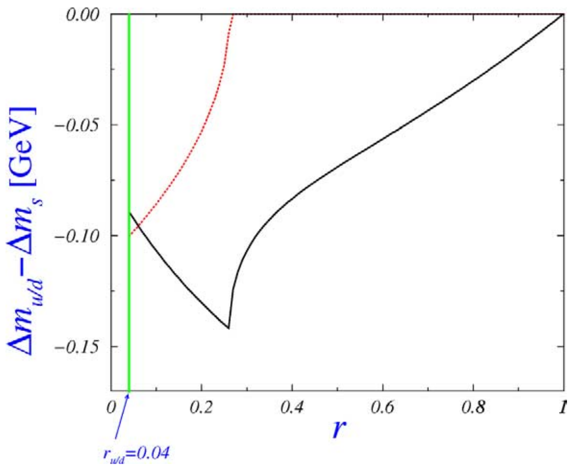

Fig. 2. Eq. (23) against the variation of $r = m_{u/d}/m_s^{\rm phys}$. The physical situations correspond to $r = 1$ and $r_{u/d} = 0.04$ [23]. We used $\Delta_S = 0.35$ GeV, the central values for the chiral couplings, as discussed in the text, and $K(1\ \text{GeV}) = 0.7\ \text{GeV}^{-1}$. The imaginary part is depicted by the dotted line which reflects the opening of the real pion emission channel $P_0^* \to P\pi$.

ative

$$\Delta m_{u/d}(0) - \Delta m_s(0) < 0, \tag{25}$$

contrary to what is experimentally established. This conclusion remains as such when varying the parameters in the ranges indicated above. The absolute value of the difference of splittings (23) depends most strongly on the value of the h-coupling and it is negative $\forall h \neq 0$. The term proportional to $g^2 - \tilde{g}^2$ is negative too. It would change the sign only if $\tilde{g}^2 > g^2$ which is beyond reasonable doubt. Notice, however, that it has been argued recently that the doublet of $\frac{1}{2}^+$ states could be the chiral partner of the $\frac{1}{2}^-$ doublet, which would imply that $\tilde{g} = g$ [24]. Even if that assumption was indeed verified in nature, our conclusion that Eq. (23) is always negative, remains true. However, as we explained above, from the present theoretical understanding the equality between the two couplings, $\tilde{g} = g$, does not appear to be plausible.[8]

5. Conclusion

In this Letter we discuss the mass difference of the scalar and pseudoscalar heavy-light mesons. Recent experimental observation by Belle and FOCUS suggests that such a difference in the charmed mesons is larger for the non-strange light quark than for the strange one, i.e.

$$\left[(m_{D_0^*} - m_D) - (m_{D_{s0}^*} - m_{D_s})\right]^{\rm exp} > 0. \tag{26}$$

Such a phenomenon cannot be explained by means of potential quark models in which this difference is almost independent of the valence light quark mass. We instead used the chiral perturbation theory to examine if the chiral enhancement suggested by experiments can indeed be reproduced. After calculating the chiral corrections, we obtain that

$$\left[(m_{D_0^*} - m_D) - (m_{D_{s0}^*} - m_{D_s})\right]^{\rm theo} < 0. \tag{27}$$

This apparent problem remains as such for any reasonable choice of the chiral couplings. It should, however, be stressed that our calculation refers to the static heavy quark ($m_Q \to \infty$) which might be questionable when discussing the charm quark sector. It is nevertheless unlikely that the $\mathcal{O}(1/m_c^n)$ corrections could change the clear qualitative result summarised in Eqs. (26), (27).

Our observations show that the scalar states are indeed peculiar. It is probable that the “quark–antiquark” picture is not adequate in case of which the unitarised meson model of Ref. [5] or the 4-quark picture for the scalar mesons [25], which enjoyed success in explaining the spectrum of light mesons, may be useful remedy in explaining the scalar states containing one heavy quark. Further experimental tests, that might prove useful in getting a more definite answer concerning the nature of the observed scalar states, were already proposed in Ref. [26].

Acknowledgements

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[8] Actually, in any Dirac equation based model, $g = \tilde{g}$ can be obtained only if one employs the free spinors and set the quark mass to zero.

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