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Molecular components in $D^*_{s0}(2317)$ and $D_{s1}(2460)$ mesons

Pablo G. Ortega[1★], Jorge Segovia[2,★★], David R. Entem[3], and Francisco Fernández[3]

[1] *CERN (European Organization for Nuclear Research), CH-1211 Geneva, Switzerland*
[2] *Technische Universität München, D-85748 Garching bei München, Germany*
[3] *Universidad de Salamanca, E-37008 Salamanca, Spain*

Abstract. Different experiments have confirmed that the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ mesons are very narrow states located, respectively, below the DK and D^*K thresholds. This is markedly in contrast with the expectations of naive quark models and heavy quark symmetry. We address the mass shifts of the $c\bar{s}$ ground states with quantum numbers $J^P = 0^+$ ($D^*_{s0}(2317)$) and $J^P = 1^+$ ($D_{s1}(2460)$) using a nonrelativistic constituent quark model in which quark-antiquark and meson-meson degrees of freedom are incorporated. The quark model has been applied to a wide range of hadronic observables and thus the model parameters are completely constrained. We observe that the coupling of the 0^+ (1^+) meson sector to the DK (D^*K) threshold is a key feature in lowering the masses of the corresponding $D^*_{s0}(2317)$ and $D_{s1}(2460)$ states predicted by the naive quark model, but also in describing the $D_{s1}(2536)$ meson as the 1^+ state of the $j_q^P = 3/2^+$ doublet predicted by heavy quark symmetry and thus reproducing its strong decay properties. Two features of our formalism cannot be address nowadays by other approaches: the coupling of the D-wave D^*K threshold in the $J^P = 1^+$ $c\bar{s}$ channel and the computation of the probabilities associated with different Fock components in the physical state.

1 Introduction

Prior to the discovery in 2003 of the $D^*_{s0}(2317)$ ($J^P = 0^+$) [1] and $D_{s1}(2460)$ (1^+) [2] resonances, the heavy-light meson sectors were reasonably well understood in the $m_Q \to \infty$ limit. In such a limit, heavy quark symmetry (HQS) holds [3]. The heavy quark acts as a static color source, its spin s_Q is decoupled from the total angular momentum of the light quark j_q and they are separately conserved. Then, the heavy-light mesons can be organized in doublets, each one corresponding to a particular value of j_q and parity. For the lowest P-wave charmed-strange mesons, HQS predicts two doublets which are labeled by $j_q^P = 1/2^+$ with $J^P = 0^+, 1^+$ and $j_q^P = 3/2^+$ with $J^P = 1^+, 2^+$. Moreover, the strong decays of the D_{sJ} ($j_q = 3/2$) proceed only through D-waves, while the D_{sJ} ($j_q = 1/2$) decays happen only through S-waves [3]. The D-wave decay is suppressed by the barrier factor which behaves as q^{2L+1} where q is the relative momentum of the two decaying mesons. Therefore, states decaying through D-waves are expected to be narrower than those decaying via S-waves.

The $D^*_{s0}(2317)$ and $D_{s1}(2460)$ mesons are considered to be the members of the $j_q^P = 1/2^+$ doublet and thus being almost degenerated and broad due to its S-wave decay. However, neither experimental values of their masses nor their empirical widths accommodate into the theoretical expectations.

★Currently at Instituto de Física Corpuscular (IFIC), CSIC-Universidad de Valencia, E-46071 Valencia, Spain
★★speaker, e-mail: jorge.segovia@tum.de

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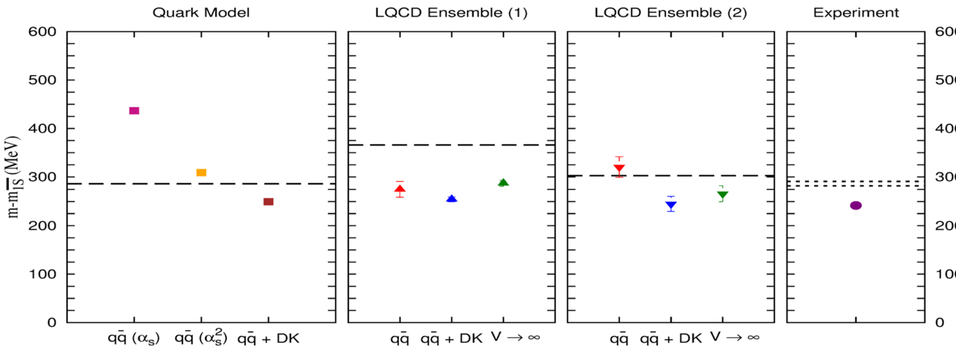

Figure 1. Energy levels from constituent quark model (CQM), from Lattice QCD [16] using Ensemble (1) and Ensemble (2), and from experiment [26]. We show, for CQM results, the quark-antiquark value taking into account the OGE potential (α_s), including its one-loop corrections (α_s^2) and coupling with the DK threshold. For the lattice QCD results, in each ensemble, we show values with just a $q\bar{q}$ interpolator basis and with a combined basis of $q\bar{q}$ and DK interpolating fields. The value of the bound $D_{s0}^*(2317)$ state position in the infinite volume limit $V \to \infty$ is obtained by an analytical continuation of the scattering amplitude combined with Lüscher's finite volume method. The dashed lines represent the threshold for DK in each approach and the dotted lines are the thresholds for D^0K^+ and D^+K^0 in experiment.

These results led to many theoretical speculations about the nature of these resonances ranging from conventional $c\bar{s}$ states [4, 5] to molecular or compact tetraquark interpretations [6–12].

Certainly quark models predict $c\bar{s}$ ground states with quantum numbers $J^P = 0^+$ and 1^+ that do not fit the experimental data. As the predictions of the quark models are roughly reasonable for other states in the charmed-strange sector [13], one must expect that the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ resonances should be modifications of the genuine $c\bar{s}$ states rather than new states out of the systematics of the quark model. On this respect, particularly relevant was the suggestion [14, 15] that the coupling of the $J^P = 0^+$ (1^+) $c\bar{s}$ state to the DK (D^*K) threshold plays an important dynamical role in lowering the bare mass to the observed value. Moreover, in a recent lattice study of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ mesons [16], good agreement with the experimental mass was found when operators for $D^{(*)}K$ scattering states are included.

In this contribution to the proceedings we present the work performed in Ref. [17][1]. Therein, we study the low-lying P-wave charmed-strange mesons using a nonrelativistic constituent quark model in which quark-antiquark and meson-meson degrees of freedom are incorporated. The constituent quark model (CQM) was proposed in Ref. [18] (see references [19] and [20] for reviews). This model successfully describes hadron phenomenology and hadronic reactions and has been recently applied to mesons containing heavy quarks (see, for instance, Refs. [21–25]).

2 Results for the $D_{s0}^*(2317)$ meson

Figure 1 compares our results for the $D_{s0}^*(2317)$ meson with the lattice QCD study of Ref. [16] and with experiment [26]. Instead of the $D_{s0}^*(2317)$ mass itself, following the lattice study, we compare the values of $m_{D_{s0}^*(2317)} - m_{\overline{1S}}$, where $m_{\overline{1S}} = 1/4(m_{D_s} + 3m_{D_s^*})$ is the spin-averaged ground state mass.

The mass of the $D_{s0}^*(2317)$ state obtained using the naive quark model and without the 1-loop corrections to the one-gluon exchange (OGE) potential is much higher than the experimental value. In this case, the $m_{D_{s0}^*(2317)} - m_{\overline{1S}} = 437\,\text{MeV}$ is almost twice the empirical figure. The mass associated

[1] All the details about the computation and the theoretical framework can be found in Ref. [17] and references therein.

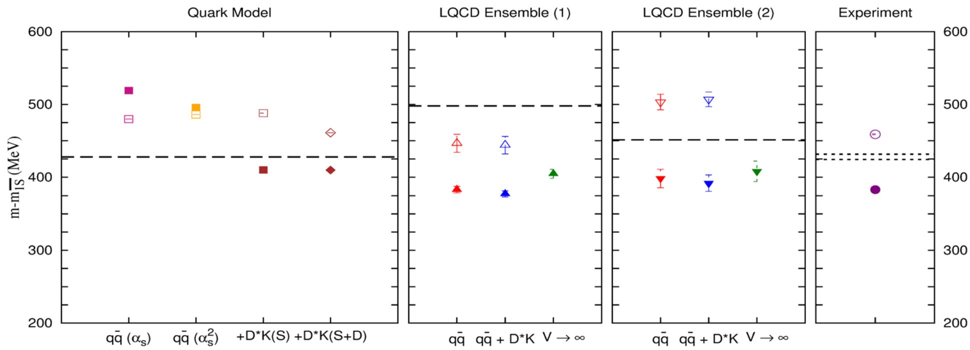

Figure 2. Energy levels from constituent quark model (CQM), from Lattice QCD [16] using Ensemble (1) and Ensemble (2), and from experiment [26]. We show, for CQM results, the quark-antiquark value taking into account the OGE potential (α_s), including its one-loop corrections (α_s^2) and coupling with the D^*K threshold in S-and D-wave. For the lattice QCD results, in each case, we show values with just a $q\bar{q}$ interpolator basis and with a combined basis of $q\bar{q}$ and D^*K interpolating fields. Remember that in the lattice QCD computations the D^*K threshold is coupled only in an S-wave. The value of the bound $D_{s1}(2460)$ state position in the infinite volume limit $V \to \infty$ is obtained by an analytical continuation of the scattering amplitude combined with Lüscher's finite volume method. This method has not been used for the $D_{s1}(2536)$ meson. The dashed lines represent the threshold for D^*K in each approach and the dotted lines are the thresholds for $D^{*0}K^+$ and $D^{*+}K^0$ in experiment.

to the $D_{s0}^*(2317)$ state is very sensitive to the α_s^2-corrections of the OGE potential. This effect brings down the $m_{D_{s0}^*(2317)} - m_{\overline{1S}}$ splitting to 309 MeV, which is now only 30% higher than the experimental value. However, as one can see in Fig. 1, the hypothetical $D_{s0}^*(2317)$ state would be above the DK threshold and thus would decay into this final channel in an S-wave making the state wider than the observed one. The mass-shift due to the α_s^2-corrections allows that the 0^+ state be close to the DK threshold. This makes the DK coupling a relevant dynamical mechanism in the formation of the $D_{s0}^*(2317)$ bound state. When we couple the 0^+ $c\bar{s}$ ground state with the DK threshold, the splitting $m_{D_{s0}^*(2317)} - m_{\overline{1S}} = 249.6$ MeV is in good agreement with experiment. Regarding the probabilities of the different Fock components in the physical state, we obtain 66% for $q\bar{q}$ and 34% for DK reflecting that the $D_{s0}^*(2317)$ meson is mostly of quark-antiquark nature in our approach.

3 Results for the $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons

Figure 2 compares our results for the $m_{D_{s1}} - m_{\overline{1S}}$ mass splitting of the first two $J^P = 1^+$ charmed-strange states with the lattice QCD study of Ref. [16] and with experiment [26].

The naive quark model predicts that the states corresponding to the $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons are almost degenerated, with masses close to the experimentally observed mass of the $D_{s1}(2536)$. The inclusion of the 1-loop corrections to the OGE potential does not improve the situation, making the splitting between the two states even smaller. Following lattice criteria, we couple first the D^*K threshold in an S-wave with the two 1^+ $c\bar{s}$ states. One can see in Fig. 2 that the state associated with the $D_{s1}(2460)$ meson goes down in the spectrum and it is located below D^*K threshold with a mass compatible with the experimental value. The state associated with the $D_{s1}(2536)$ meson is almost insensitive to this coupling because it is the $J^P = 1^+$ member of the $j_q = 3/2$ doublet predicted by HQS and thus it couples mostly in a D-wave to the D^*K threshold. Lattice QCD has not yet computed the coupling in D-wave of the D^*K threshold with the 1^+ $c\bar{s}$ sector. This coupling is trivially implemented in our approach. The state associated with the $D_{s1}(2460)$ meson experience a very small modification because it is almost the $|1/2, 1^+\rangle$ eigenstate of HQS, whereas the state associated with $D_{s1}(2536)$ meson suffers a moderate mass-shift approaching to the experimental value.

When the D^*K threshold is coupled, the meson-meson component is around 50% for both $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons. It is also relevant to realize that the quark-antiquark component in the wave function of the $D_{s1}(2536)$ meson holds quite well the $^1P_1$ and $^3P_1$ composition predicted by HQS, which is crucial in order to have a very narrow state and describe well its decay properties.

4 Summary

We have performed a coupled-channel computation taking into account the $D^*_{s0}(2317)$, $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons and the DK and D^*K thresholds within the framework of a constituent quark model. Our method allows to introduce the coupling with the D-wave D^*K channel and the computation of the probabilities associated with the different Fock components of the physical state.

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