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Implication of chiral symmetry on charm meson spectroscopy

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Abstract. It is demonstrated that, if the lightest positive parity charm mesons are assumed to owe their existence to non-perturbative Goldstone boson-D/D^* scattering, various puzzles in the charm meson spectrum get resolved. Most importantly the ordering of the lightest strange and non-strange scalars becomes natural. Furthermore, it is demonstrated that the amplitudes for Goldstone boson-D/D^* scattering are fully consistent with the high quality data on decay $B^- \to D^+\pi^-\pi^-$ provided by LHCb. It implies that the lowest positive-parity charm mesons are dynamically generated rather than quark-antiquark states.

1 Introduction

Understanding the nonperturbative aspects of the QCD is one of the most challenging problems in physics. Quarks and gluons are confined in color-neutral hadrons. Therefore, one can tackle the challenge by studying hadron spectroscopy. Until the beginning of the millennium heavy-hadron spectroscopy was assumed to be well understood by the conventional quark model which describes the positive-parity ground-state charm mesons as bound systems of a heavy quark and a light antiquark in a P-wave. However, it has been put into question since the discovery of the charm-strange mesons $D^*_{s0}(2317)$ [1] and $D_{s1}(2460)$ [2]. They are significantly lighter than their quark model expectations [3, 4]. It is also noticed that the mass difference between the $D^*_{s0}(2317)$ and the $D_{s1}(2460)$ is equal to that between the ground-state pseudoscalar D^+ and the vector D^{*+} within in 2 MeV. Since attempts to adjust the quark model to adapt the two new states is at odds with previous expectations and raises new puzzles [5], various interpretations of the nature of the $D^*_{s0}(2317)$ and the $D_{s1}(2460)$ were proposed, including $D^{(*)}K$ hadronic molecules (loosely bound states of two hadrons) [6–8], tetraquark (compact states made of two quarks and two antiquarks) [9, 10], and chiral partners (doublets due to the chiral symmetry breaking of QCD in heavy-light systems) [11, 12]. The situation became more obscure in 2004 when two new charm-nonstrange mesons, i.e. $D^*_0(2400)$ [13, 14] and $D_1(2430)$ [13], were discoveried. Their quantum numbers suggest that they should be the SU(3) partners of the $D^*_{s0}(2317)$ and $D_{s1}(2460)$, respectively. Briefly, the experimental observations brought up three puzzles:

(1) Why are the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ much lighter than the quark model expectations?

(2) Why is the mass difference between the $D_{s1}(2460)$ and the $D^*_{s0}(2317)$ equal to that between the D^{*+} and D^+ within 2 MeV?

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(3) Why are the $D_0^*(2400)$ and $D_1(2430)$ masses almost equal to or even higher than their strange siblings, although states with an additional strange quark are typically at least 100 MeV heavier since $m_s/m_d \simeq 20$, see, e.g., Ref. [15]?

In recent works it was demonstrated that analyses combining effective field theory with Lattice QCD calculations allows one to resolve all those puzzles. It suggests that all low-lying positive-parity charm mesons are dynamically generated as hadronic molecules. One reason why the resonance parameters of the $D_0^*(2400)$ and $D_1(2430)$ in the Review of Particle Physics (RPP)[16] should be questioned is that the standard Breit-Wigner (BW) amplitudes used are inconsistent with the constraint from the chiral symmetry, which calls for energy-dependent vertices. However, a BW form uses a constant vertex which would lead to a value of the mass larger than its real value, see e.g. in Ref. [17]. Moreover, the energy range of these states overlaps with various thresholds which need to be taken into account in a sound way. A theoretical framework satisfying such requirements is provided by the unitarized chiral perturbation theory (ChPT) for charmed mesons, see e.g. Refs. [8, 18–24]. In this approach, ChPT at a given order is used to calculate the interaction potential which is then resummed for the S-channel to fulfill exact two-body unitarity and allows for the generation of resonances (including bound states). Without the experimental data on the Goldstone boson (ϕ)-D/D^* scattering, the low-energy constants (LECs) of the ChPT can be determined by comparing with the LQCD results, see e.g. in Refs. [20, 22–25], or estimated using the resonance-exchange model, see e.g. Refs. [26, 27].

With the Lüscher formalism and its extension to the coupled-channnels, scattering lengths and phase shifts for the D-ϕ interaction were obtained at unphysical quark masses, see e.g. in Refs. [20, 28–32]. For the early studies using only $c\bar{s}$-type interpolators with $J^P = 0^+$, it gave a mass significantly larger than the observed $D_{s0}^*(2317)$ [33, 34]. Using both DK as well as $c\bar{s}$ interpolating fields, the $D_{s0}^*(2317)$ was found 37(17) MeV below the DK threshold in Ref. [34], where the simulation is done on $N_f = 2 + 1$ gauge configurations with $m_\pi \simeq 156$ MeV and the resulting $M_{D_{s0}^*} - (M_{D_s} + 3M_{D_s^*})/4 = 266(16)$ MeV is close to the experimental value 241.5(0.8) MeV. In Ref. [35], a new calculation with an almost physical pion mass $M_\pi = 150$ MeV, the masses of the $J^P = 0^+$ and 1^+ charm-strange mesons are obtained as 2348(4)(6) MeV and 2451(4)(1) MeV, respectively. They are close to their corresponding experimental values, i.e. 2317.7(0.6)(2.0) MeV and 2459.5(0.6)(2.0) MeV. Notice that the Lattice results are slightly higher than the experimental values is because the pion and D and D^* masses used in simulation are slightly larger than experimental ones. For the nonstrange sector, using both $D\pi$ and $c\bar{q}$ interpolators, the extracted BW mass of $D_0^*(2400)$ is 351(21) MeV above the spin average $(M_D + 3M_{D^*})/4$, in agreement with the experimental value of 347(29) MeV above, in Ref. [29], where a single two-flavor dynamical ensemble with $M_\pi \approx 266$ MeV is used.

The first Lattice calculation on the $D\pi$ scattering lengths was performed in Ref. [20], where only the channels free of disconnected Wick contractions are concerned, i.e. $D\pi$ with isospin $I = 3/2$, $D\bar{K}$ with $I = 0, 1$, D_sK and $D_s\pi$. In Ref. [20], the obtained scattering lengths are used to fix the next-leading order (NLO) LECs in ChPT Lagrangian. In particular, with the determined LECs, the attraction in channel $(S, I) = (1, 0)$ is sufficiently strong to form a bound state at 2315^{+18}_{-28} MeV, which corresponds to $D_{s0}^*(2317)$. The ChPT for charmed mesons were extended to next-to-next-to-leading order (NNLO) in Refs. [22, 24, 36–40]. The first lattice QCD study of coupled-channel $D\pi$, $D\eta$ and $D_s\bar{K}$ scattering in isospin-1/2 was performed in Ref. [32], in which the t-matrix was parameterized by a coupled-channel K-matrix and a pole located below the $D\pi$ threshold was reported. Since it was worked at $M_\pi \approx 391$ MeV, it is interesting to figure out the relationship between this bound state and the $D_0^*(2400)$. In Ref. [23], with the lattice scattering lengths of disconnected Wick contrac-

tions in Ref. [20] and chiral extrapolation, it is shown that the bound state at $M_\pi = 391$ MeV corresponds to a resonance with pole position $2114^{+3}_{-3} - i111^{+8}_{-7}$ MeV at physical pion mass. In addition, the $D^*_{s0}(2317)$ emerges naturally with a mass 2321^{+6}_{-3} MeV. Moreover, the predicted finite volume energy levels for $(S, I) = (1, 0)$, $J^P = 1^+$ and 0^+, and $(S, I) = (0, 1/2)$ successfully describe the lattice results [41, 42]. It indicates that the unitarized amplitudes from ChPT are reliably based on QCD, which can be used to study the possible dynamically generated resonances. In particular, two scalar $I = 1/2$ states are found with the lighter one located more than 100 MeV below its corresponding strange partner [8, 18, 23, 41, 43]. It suggests that the particle listed as $D^*_0(2400)$ in RPP should correspond to two resonances with pole positions $2105^{+6}_{-8} - i\ 102^{+12}_{-12}$ MeV and $2451^{+36}_{-26} - i\ 134^{+7}_{-8}$ MeV [41, 44], respectively. In brief, the combination of EFT methods and lattice QCD provides us a sound solution to the three puzzles in charm spectrum: the $D^*_{s0}(2317)$ and $D_{s1}(2460)$ are dominantly DK and D^*K hadronic molecules, respectively; heavy-quark spin symmetry predicts that the binding energies are independent of the heavy meson spin up to an uncertainty of about 10%. Moreover, there are two resonances in the $(S, I) = (0, 1/2)$ channel with the lighter one located more than 100 MeV below its strange partner. Given the above discussion, it is important to test the picture outlined above as much as possible. In the following, we demonstrate that our resolution to these puzzles is backed by precise experimental data.

2 Comparison with experimental data on decay $B^- \to D^+\pi^-\pi^-$

At the quark level, the LO effective weak Hamiltonian $H_{\rm eff}$ describing the process $B^- \to D^+\pi^-\pi^-$, which is the best data providing access to the $D\pi$ system at present [45], can be written as

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} V^*_{cb} V_{ud} (C_1(\mu)\mathcal{O}^d_1 + C_2(\mu)\mathcal{O}^d_2) + (b \to s) + \text{h.c.}, \tag{1}$$

with G_F the Fermi constant, V_{ij} the elements of the famous CKM matrix, and $C_i(\mu)$ the scale-dependent Wilson coefficient. Here the tree-level operators read

$$\begin{aligned} \mathcal{O}^d_1 &= (\bar{c}_a b_b)_L (\bar{d}_b u_a)_L, \\ \mathcal{O}^d_2 &= (\bar{c}_a b_a)_L (\bar{d}_b u_b)_L, \end{aligned} \tag{2}$$

with the subscript a and b color indices. The subscript L indicates that only the left-hand components of quarks are involved in. The Hamiltonian $H_{\rm eff}$ is not invariant under the chiral rotation. However, we can make it chirally invariant by introducing a spurion

$$H = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ V_{us}/V_{ud} & 0 & 0 \end{pmatrix} \tag{3}$$

which transforms under chiral symmetry as $H \mapsto g_L H g^\dagger_L$.

Since we are only interested in the low $D\pi$-energy region, the soft pion can be regarded as a Goldstone boson and the hard pion moving fast is treated as a matter field which transform homogeneously. With the chirally invariant Hamiltonian, one can construct a chiral effective Lagrangian describing the decay process $B^- \to (D_{(s)}\phi)\pi^-$, see e.g. in Ref. [44]. When the low $D\pi$ mass region is concerned, it is sufficient to consider the amplitude with S-, P-, and D-waves. For the P- and D-wave amplitudes, the same BW form as in the LHCb analysis [45] are used. Taking both the final-state-interactoin as well as the coupled-channel effects

from $D\pi$, $D\eta$ and $D_s^+K^-$ into account, one arrives at the S-wave amplitude [44]

$$\mathcal{A}_0(s) \propto \Big\{E_\pi\Big[2 + G_1(s)\Big(\frac{5}{3}T_{11}^{1/2}(s) + \frac{1}{3}T^{3/2}(s)\Big)\Big] + \frac{1}{3}E_\eta G_2(s)T_{21}^{1/2}(s) + \sqrt{\frac{2}{3}}E_K G_3(s)T_{31}^{1/2}(s)\Big\} + CE_\eta G_2(s)T_{21}^{1/2}(s), \tag{4}$$

where C is a LEC from the effective Lagrangian. Here the $T_{ij}^I(s)$ are the S-wave $D\phi$ scattering amplitudes for the coupled-channel system with total isospin I, where i, j are channel indices with 1, 2 and 3 referring to $D\pi$, $D\eta$ and $D_s\bar{K}$, respectively. The $G_i(s)$ function is evaluated via a once-subtracted dispersion relation. It is easy to check that the amplitude (4) satisfies the chiral symmetry and unitarity. We fit to the so-called angular moments, see e.g., Refs. [44, 45], since they contain important information about the partial-wave phase variations. We include the resonances D^* and $D^*(2680)$ in P-wave and $D_2(2460)$ in the D-wave with the BW parameters fixed as the central values in Ref. [45]. A comparison of the best fit with the LHCb data is shown in Fig. 1 together with the best fit provided by the LHCb analysis. It is

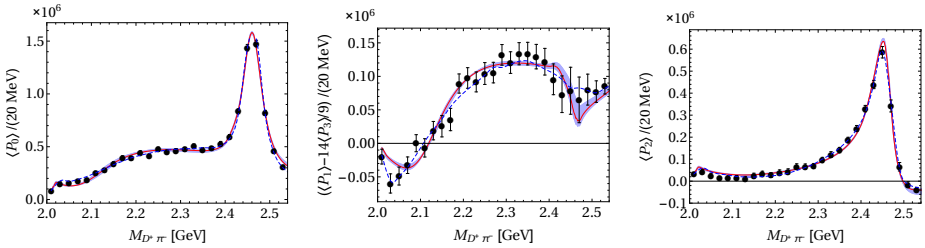

Figure 1. Fit to the LHCb data for the angular moments $\langle P_0\rangle$, $\langle P_1\rangle - 14\langle P_3\rangle/9$ and $\langle P_2\rangle$ for the $B^- \to D^+\pi^-\pi^-$ reactions [44, 45].

worth mentioning that in $\langle P_1\rangle - 14\langle P_3\rangle/9$, where the $D_2(2460)$ does not play any role, the data show a significant variation between 2.4 and 2.5 GeV. This feature can be understood as the signal for the opening of the $D^0\eta$ and $D_s^+\pi^-$ thresholds, respectively. Moreover, the LHCb Collaboration provides more detailed information on the S-wave amplitude in Ref. [45]. In Fig. 2, it is clear that the S-wave amplitude determined by the fit is fully consistent with the one extracted from the data for $B^- \to D^+\pi^-\pi^-$ by the LHCb Collaboration.

3 Summary

In summary, we have demonstrated that the amplitudes determined by the combination of the EFT methods and Lattice QCD calculations provides us a natural solution to the puzzles in charm meson spectrum. They are fully consistent with recent high quality LHCb data on decay $B^- \to D^+\pi^-\pi^-$ which provides by far the most precise experimental information on the $D\pi$ system. The $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are dominantly DK and D^*K molecular states, respectively. Heavy quark spin symmetry indicates that they should have the same binding energy with an uncertainty around 10%. Most importantly, each of the $D_0^*(2400)$ and $D_1(2430)$ in RPP should be replaced by two states with the lighter one located more than 100 MeV below its strange sibling. This coherent picture clearly calls for a change of the paradigm for the positive-parity charmed mesons: The lowest positive-parity states

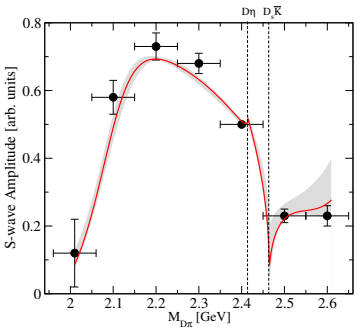

Figure 2. Comparison of the the S-wave amplitude determined in Ref. [44] with the one extracted in the experimental analysis in Ref. [45].

need to be considered as dynamically generated two-hadron states as opposed to a simple quark-antiquark structure.

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