Exotic hadrons with heavy quarks in EFT approach

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Summary. — The approach to exotic hadrons with heavy quarks based on the Effective Field Theory is reviewed and its application to particular near-threshold exotic states in the spectrum of charmonium and bottomonium is discussed.

1. – Hadronic physics before and after 2003

Before 2003, the general consensus in hadronic physics was that the quark model could provide a decent description of low-lying hadrons (quark-antiquark mesons and three-quark baryons) known at that time. For the hadrons consisting of heavy quarks a simpler nonrelativistic approach could be employed while relativistic corrections could further improve the description. The experiment gradually filled "missing states" predicted by the quark model, and lattice calculations provided additional (alternative) source of information on hadronic states. However, in 2003 the Belle Collaboration observed the first state in the spectrum of charmonium with the properties at odds with the predictions of the quark model [1]. This state was named $X(3872)$, with the letter X from the end of the Latin alphabet emphasising its unusual nature. Since then, the number of such unconventional hadrons with heavy quarks grows fast, and a new branch of hadrons spectroscopy is established — the physics of the exotic XYZ states. A recent review of the experimental and theoretical status of such hadrons can be found in [2].

2. – Effective field theory approach to exotic states

Most of exotic hadronic states in the spectrum of heavy quarkonium are located near S-wave strong open-flavour thresholds which, therefore, should leave a strong imprint on their nature and properties. The closer an exotic state resides to such a threshold the larger is the probability to observe it in the corresponding two-hadron channel. If this probability is close to unity, the possible compact component of the wave function can be neglected, and the resulting approach to exotic hadrons is known as the molecular

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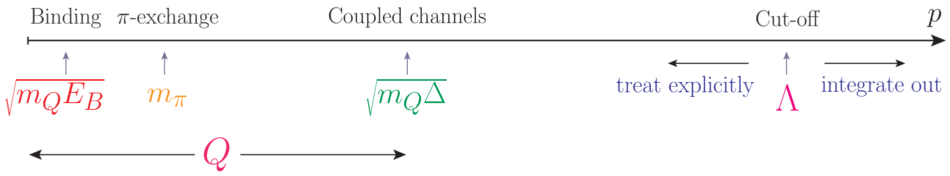

Fig. 1. – The hierarchy of the scales relevant for the EFT for exotic hadrons with heavy quarks.

model — see the review [3]. A promising approach to hadronic molecules is based on Effective Field Theory (EFT). In this approach, all the dynamics with the intrinsic momenta above some chosen hard scale Λ are integrated out while all the dynamics with the intrinsic momenta $Q < \Lambda$ are treated explicitly — see Fig. 1 for a sketch of the typical hierarchy of the scales relevant for EFT for exotic hadrons with heavy quarks. The convergence parameter of the resulting theory is given by the ratio Q/Λ, so that predictions of such theory can be systematically improved by considering higher orders in the this expansion. Then the interaction potential V between heavy hadrons is built to include all relevant interactions, comply with all relevant symmetries, and incorporate coupled-channel dynamics, if the applicability domain of the theory is to cover several hadronic thresholds. This potential is then expanded in powers of p^2/Λ^2 (with p for the relative momentum between hadrons), truncated at necessary order (LO, NLO...), and used as the kernel of the (multichannel) Lippmann-Schwinger equation $T = V - VGT$ for the scattering amplitude T. The free parameters of this amplitude (low-energy constants and couplings to hadronic channels) are fitted to the existing experimental data (two-dimensional Dalitz plots, their one-dimensional projections, measured branching fractions, and so on). The information on the exotic states can then be extracted from the amplitude T by searching for its poles on the complex energy plane (with the "mass" and "width" of the exotic state associated with the real and twice the imaginary part of the pole, respectively), evaluating residues at the poles, and so on. For the quarks sufficiently heavy in comparison with the typical QCD scale, $m_Q \gg \Lambda_{\rm QCD}$, their spins decouple from the rest of the dynamics of the system that results in the Heavy Quark Spin Symmetry (HQSS) — a strong theoretical tool that allows one to interrelate the properties of the hadronic states with different orientations of the heavy quark spins. In particular, the properties of the so-called spin partner states can be predicted in a model-independent and parameter-free way using the parameters of the interaction extracted from the fit to the existing experimental data.

3. – Z_b states in the spectrum of bottomonium

In 2011 the Belle Collaboration observed a pair of charged exotic states in the spectrum of bottomonium residing in a close vicinity of the open-bottom thresholds $B\bar{B}^*$ and $B^*\bar{B}^*$ [4]. A molecule assignment for the Z_b's [5],

$$\begin{aligned} Z_b(10610) &\sim B\bar{B}^* \sim 0^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} + 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}, \\ Z_b'(10650) &\sim B^*\bar{B}^* \sim 1^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} - 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q} \end{aligned} \tag{1}$$

allowed to explain comparable dipion decay widths from $\Upsilon(10860)$ to the final states containing Υ and h_b bottomonia. Since the latter transitions require a heavy quark spin flip while the former do not, a naive expectation would be a two-order-of-magnitude suppression in the latter case. Meanwhile, it follows from (1) that, in the molecular picture, the Z_b states contain both spin-0 and spin-1 contributions for the heavy-quark pair, so the transitions from $\Upsilon(10860)$ can proceed through one of them or the other without suppression. It is instructive to notice, however, that in the exact HQSS limit the destructive interference in the $\pi\pi h_b$ channels (the terms $0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}$ in (1)) would result in a strong cancellation and, therefore, strong suppression of the corresponding probability as compared with that of the transitions to the $\pi\pi\Upsilon$ final states where the interference is constructive (the terms $1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q}$ in (1)). In actuality HQSS is explicitly broken by the B^*-B mass splitting that is large enough to have only weakly overlapping Z_b and Z_b' structures of the width Γ_{Z_b}. It was demonstrated in [6] that the actual ratio $(m_{Z_b'} - m_{Z_b})/\Gamma_{Z_b} \simeq 3$ is sufficient to explain the experimental branchings ratio.

The coupled-channel EFT approach developed for the Z_b states in [7, 8] allowed to perform a combined fit to the Belle data in all 7 measured production and decay channels, $\Upsilon(10860) \to \pi Z_b^{(\prime)} \to \pi B\bar{B}^{(*)}$, $\pi\pi h_b(1,2P)$, $\pi\pi\Upsilon(1,2,3S)$, and make model-independent and parameter-free predictions for the spin partners W_{bJ} with the quantum numbers J^{++} $(J = 0, 1, 2)$ taking into account coupled channels as well as various effects related with the pions dynamics and their interaction in the final state [9]. Such spin partner states are expected to be produced in radiative decays from $\Upsilon(10860)$ [5] and, hopefully, observed in the high-luminosity and high-statistic data from the Belle II experiment [10].

4. – Z_{cs} state(s) in the spectrum of charmonium

Recently the BESIII Collaboration announced the first observation of a charged exotic state with open strangeness in the spectrum of charmonium [11]. In particular, the parameters of the new hadron $Z_{cs}(3982)$ observed in the reaction $e^+e^- \to K^+\left[D_s^- D^{*0} + D_s^{*-} D^0\right]$ where extracted as $M = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV and $\Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV.

A coupled-channel theoretical analysis of the BESIII data performed in [12] led to identification of two possible scenarios: (i) the new $Z_{cs}(3982)$ is related by the flavour $SU(3)$ symmetry with $Z_c(3900)$ [13], and its spin partner Z_{cs}' is likely to exist near the $D_s^* D^*$ threshold; (ii) the $Z_c(4020)$ and $Z_c(3900)$ are not related by HQSS, so the new state $Z_{cs}(3982)$ is still related with $Z_c(3900)$ by the flavour $SU(3)$ symmetry, however it should have no spin partner. The experimental situation with the existence of an exotic state near the $D_s^* D^*$ threshold is still obscure — although the BESIII data hint its possible existence [14], the significance of the new structure is low for a definite conclusion. If the Z_{cs}' state is confirmed at a higher statistics, this will imply that either the first scenario above is realised in nature or, according to the second scenario, this state is completely unrelated to the $Z_{cs}(3982)$. Meanwhile, the latter possibility requires a very delicate fine tuning of the parameters of the theory and, therefore, looks less plausible than the first scenario that is, therefore, more general and probable.

5. – Double-charm state T_{cc}^+

A narrow double-charm near-threshold state T_{cc}^+ was recently observed and studied by the LHCb Collaboration [15, 16]. It was found to be an isoscalar with the quantum numbers $J^P = 1^+$, that hints its minimal quark content to be $cc\bar{u}\bar{d}$ with the clustering dictated by the molecular model. Namely, the T_{cc}^+ is most likely to be a $D^{*+}D^0/D^{*0}D^+$

mixture with the dominating former component given the proximity of the state to the corresponding threshold. Despite obvious similarities between the T_{cc}^{+} and $X(3872)$, the difference between them is crucial. Namely, since the X contains a $c\bar{c}$ pair while the T_{cc}^{+} contains a cc pair, the former can decay into hidden-charm final states while the latter can not. As a result, the only hadronic decay mode of the T_{cc}^{+} is stipulated by the decay $D^* \to D\pi$. Also, if a short-range core exists in the wave functions of these two exotic hadrons, it can potentially be associated with a generic $c\bar{c}$ charmonium in case of the X and with a compact tetraquark $cc\bar{q}\bar{q}$ in case of the T_{cc}^{+}.

A coupled-channel EFT-based analysis of the T_{cc}^{+} was performed in [17] and the important role of the pion exchange was emphasised and studied in detail. The low-energy expansion of the amplitude for near-threshold states was discussed in [18] at the example of the T_{cc}^{+}. Finally, in [19], the properties of the T_{cc}^{+} at a unphysically large pion mass were investigated in relation with the first study of this state on the lattice performed in [20]. Further details of the EFT approach to the T_{cc}^{+} can be found in [21].

6. – Exotic states in the double-charmonium spectrum

Recent studies of the double-J/ψ production in proton-proton collisions performed by the LHCb Collaboration revealed a nontrivial energy dependence of the corresponding line shape in the energy range from the double-J/ψ threshold at 6.2 GeV to approximately 7.2 GeV [22]. In [23] these data were analysed in the framework of a coupled-channel approach. It was found that the rises and dips in the line shape can be understood as a result of an interplay of the $J/\psi J/\psi$, $J/\psi\psi(2S)$, and $J/\psi\psi(3770)$ channels. In addition, the poles of the resulting unitary amplitude were searched for on the energy complex plane. It was concluded that the LHCb data could not unambiguously fix the position of the pole near 6.9 GeV. Further inclusion of the recent CMS [24] and ATLAS [25] data on the double-J/ψ production into the combined fit may improve the pole extraction. This pole was given the name $X(6900)$ and it is actively discussed in the literature. In the meantime, a robust prediction of the coupled-channel models employed in [23] is the existence of a pole, named the $X(6200)$, in a close vicinity of the double-J/ψ threshold. The nature of the corresponding physical state was demonstrated to be consistent with a double-J/ψ molecule [26] or with a compact fully charmed tetraquark [27]. However, in the latter case, the stability of such an object remains unclear given the results reported in [28]. Further discussions of the double-J/ψ spectrum can be found in [29].

7. – Conclusions

Collider experiments at the energies above the open-flavour threshold started a new era in the hadronic physics of heavy quark flavours. In this energy region the typical line shapes have a non-Breit-Wigner form and threshold phenomena, coupled channels, and pion exchange are important and can not be disregarded in the analysis. In order to arrive at reliable conclusions and predictions, multibody unitarity and analyticity of the amplitude need to be preserved. EFT provides a model-independent and systematically improvable analysis and prediction tool, with its results regarded as input for QCD-inspired models. Lattice simulations of exotic states are important to fill the gaps in the existing experimental data and provide information on the Universes with different values of physical parameters.

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