MESON SPECTROSCOPY: TOO MUCH EXCITEMENT AND TOO FEW EXCITATIONS*

George Rupp, Susana Coito

Centro de Física das Interacções Fundamentais, Instituto Superior Técnico
Technical University of Lisbon, 1049-001 Lisboa, Portugal

Eef van Beveren

Centro de Física Computacional, Departamento de Física
Universidade de Coimbra, 3004-516 Coimbra, Portugal

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We briefly review the general status of meson spectroscopy, especially in light of the often made claim that there are too many observed resonances to be accounted for as $q\bar{q}$ states. Also, the adequacy of the usual Coulomb-plus-linear, alias "funnel", confining potential for reproducing the experimental spectra of light, heavy–light, and heavy mesons is critically analysed. Thus, many serious discrepancies are observed and discussed. As possible causes, we suggest the neglect of unitarisation and other coupled-channel effects, as well as the deficiency of the funnel potential itself. In order to illustrate our alternative, "unquenched" approach, we present some recent examples of successfully described puzzling mesonic enhancements and resonances, such as the charmonium states $X(4260)$ and $X(3872)$, as well as the axial-vector charmed mesons $D_1(2420)$, $D_1(2430)$, $D_{s1}(2536)$, and $D_{s1}(2460)$.

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1. Brief review of the meson spectrum

Contrary to widespread belief, there are not too many observed [1] mesonic resonances to be accounted for by normal quark–antiquark states, which is the usually invoked argument to justify the introduction of exotic, *i.e.*, non-$q\bar{q}$, configurations. The reasons why newly detected mesonic enhancements often seem to be incompatible with $q\bar{q}$ states can be manifold:

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1. the underlying confining potential may be different from what is generally taken for granted, as often demonstrated by us (see *e.g.* Ref. [2]);
2. mass shifts due to unitarisation (or "unquenching") are mostly neglected or underestimated (see *e.g.* Ref. [3]);
3. unitarisation sometimes even yields extra, dynamically generated resonances, which nevertheless have a $q\bar{q}$ source (see *e.g.* Ref. [4]);
4. the opening of strong decay thresholds generally distorts the line shapes of nearby resonances, or can even by itself give rise to enhancements that look like resonances (see *e.g.* Ref. [5]);
5. large inelasticity effects between observed OZI-forbidden decays and non-observed OZI-allowed ones can lead to signal depletion at true resonances and/or thresholds, resulting in non-resonant apparent enhancements in between (see *e.g.* Ref. [6]).

In this paper, an short assessment will be made of the status of meson spectroscopy. As theoretical benchmark, we shall take what many consider a kind of "standard model" of mesons, *viz.* the celebrated and topcited relativised model of Godfrey and Isgur (GI) [7], which features the ususal Coulomb-plus-linear confinement forces, also called "funnel" potential, and an explicit one-gluon-exchange term generating spin–spin and spin–orbit splittings. After showing numerous discrepancies between the predictions of the GI model and data [1], we shall review an alternative description of three controversial mesonic systems, namely the $X(4260)$ [1] and $X(3872)$ [1] charmonium structures, as well as the $D_{s1}(2460)$ [1] charmed–strange meson. These states cannot be described correctly by the GI or any other quenched $q\bar{q}$ model, giving rise to the usual "poor-man's" explanation in terms of exotics or crypto-exotics. Below, we shall show how our unitarised Resonance-Spectrum Expansion [8] manages to explain $X(4260)$ as a non-resonant enhancement [6], and reproduce the true resonances $X(3872)$ [9] and $D_{s1}(2460)$ [10], together [10] with the other axial-vector charmed mesons $D_{s1}(2536)$, $D_1(2430)$, and $D_1(2420)$ [1].

1.1. Observed meson spectum and Godfrey–Isgur [7] model

The GI [7] quark model for mesons is still very frequently referred to for comparison when new resonances are observed or other models make predictions. This is understandable in view of the GI model's completeness in predicting meson spectra for almost any desired flavour combinations and quantum numbers, besides the employment of the widely accepted funnel potential. Thus, it appears opportune to briefly reassess this 27-year-old model in the light of present-day meson spectra as interpreted by the PDG [1] collaboration, identifying some of the outstanding problems.

1.1.1. Light-quark isoscalar mesons

- $0^{++}/{}^3P_0$:
  Lowest GI scalar ~ 600 MeV heavier than $\boldsymbol{f_0(600)}$[1] (alias $\boldsymbol{\sigma}$);
  GI $s\bar{s}$ scalar almost 400 MeV heavier than $\boldsymbol{f_0(980)}$.
- $2^{++}/{}^3P_2$–${}^3F_2$: PDG listings report 6 likely $n\bar{n}$ ($n = u, d$) states up to ≈ 2.15 GeV, *viz.* $\boldsymbol{f_2(1270)}$, $f_2(1565)$, $f_2(1640)$, $f_2(1810)$, $f_2(1910)$, and $f_2(2150)$, whereas GI only predict 3. In probably dominant $s\bar{s}$ sector, PDG also lists 6 states up to ≈ 2.35 GeV: $f_2(1430)$, $\boldsymbol{f_2'(1525)}$, $\boldsymbol{f_2(1950)}$, $\boldsymbol{f_2(2010)}$, $\boldsymbol{f_2(2300)}$, and $\boldsymbol{f_2(2340)}$, while GI again only predict 3.
  Note: some PDG f_2 states may not be resonances [11], but $f_2(1565)$ looks reliable. Also, PDG: $m(2\,{}^3P_2) - m(1\,{}^3P_2) \approx 300$ MeV;
  GI: $m(2\,{}^3P_2) - m(1\,{}^3P_2) = 540$ MeV.
  For unknown reasons, PDG omits $f_2(1565)$ from the Summary Table.
- $1^{+-}/{}^1P_1$:
  PDG $n\bar{n}$ entries: $\boldsymbol{h_1(1170)}$, $h_1(1595)$;
  GI predict: $h_1(1220)$ $(1\,{}^1P_1)$, $h_1(1780)$ $(2\,{}^1P_1)$.

1.1.2. Light-quark isovector mesons

- $0^{++}/{}^3P_0$:
  PDG entries: $\boldsymbol{a_0(980)}$, $\boldsymbol{a_0(1450)}$;
  GI: $a_0(1090)$ $(1\,{}^3P_0)$, $a_0(1780)$ $(2\,{}^3P_0)$.
- $1^{++}/{}^3P_1$:
  PDG entries: $\boldsymbol{a_1(1260)}$, $a_1(1640)$;
  GI: $a_1(1240)$ $(1\,{}^3P_1)$, $a_1(1820)$ $(2\,{}^3P_1)$.
- $2^{++}/{}^3P_2$:
  PDG entries: $\boldsymbol{a_2(1320)}$, $a_2(1700)$;
  GI: $a_2(1310)$ $(1\,{}^3P_2)$, $a_2(1820)$ $(2\,{}^3P_2)$.
- $1^{--}/{}^3S_1$–${}^3D_1$:
  PDG entries: $\boldsymbol{\rho(1450)}$, $\rho(1570)$, $\boldsymbol{\rho(1700)}$, $\rho(1900)$;
  GI: $\rho(1450)$ $(2\,{}^3S_1)$, $\rho(1660)$ $(1\,{}^3D_1)$, $\rho(2000)$ $(3\,{}^3S_1)$, $\rho(2150)$ $(2\,{}^3D_1)$.
  Note: a recent analytic S-matrix analysis [12] arrived at assignments quite different from both PDG and GI: $\rho(1250)$, $\rho(1470)$, $\rho(1600)$, $\rho(1900)$. Also, it concluded that only $\rho(1250)$ and $\rho(1600)$ are crucial to describe the phase shifts, whereas $\rho(1900)$ and, to a lesser extent, $\rho(1470)$ improve the inelasticity. For mysterious reasons, PDG conceals $\rho(1250)$ under the $\boldsymbol{\rho(1450)}$ entry [1].

[1] Henceforth, we shall print the states included in the PDG Summary Table [1] in boldface.

1.1.3. Strange mesons

- $0^-/{}^1S_0$:
  PDG entries: $K(1460)$, $K(1830)$;
  GI: $K(1450)$ $(2\,{}^1S_0)$, $K(2020)$ $(3\,{}^1S_0)$.

- $0^+/{}^3P_0$:
  PDG entries: $K_0^*(800)$, $\boldsymbol{K_0^*(1430)}$, $K_0^*(1950)$;
  GI: $K_0^*(1240)$ $(1\,{}^3P_1)$, $K_0^*(1890)$ $(2\,{}^3P_1)$.

- $1^-/{}^3S_1-{}^3D_1$:
  PDG entries: $\boldsymbol{K^*(1410)}$, $\boldsymbol{K^*(1680)}$;
  GI: $K^*(1580)$ $(2\,{}^3S_1)$, $K^*(1780)$ $(1\,{}^3D_1)$.

- $1^+/{}^3P_1-{}^1P_1$:
  PDG entries: $\boldsymbol{K_1(1270)}$, $\boldsymbol{K_1(1400)}$, $K_1(1650)$;
  GI: $K_1(1340)$ $(1\,{}^1P_1)$, $K_1(1380)$ $(1\,{}^3P_1)$, $K_1(1900)$ $(2\,{}^1P_1)$, $K_1(1930)$ $(2\,{}^3P_1)$.

- $2^-/{}^1D_2$-${}^3D_2$:
  PDG entries: $K_2(1580)$, $\boldsymbol{K_2(1770)}$, $\boldsymbol{K_2(1820)}$, $K_2(2250)$;
  GI: $K_2(1780)$ $(1\,{}^1D_2)$, $K_2(1810)$ $(1\,{}^3D_2)$, $K_2(2230)$ $(2\,{}^1D_2)$, $K_2(2260)$ $(2\,{}^3D_2)$.

1.1.4. Summary of light mesons

The light-meson spectrum [1] appears to favour radial splittings that are considerably smaller than those predicted by the GI and similar funnel models, as well as lattice QCD [13]. There is no indication that some of the observed resonances might be crypto-exotics, so that no excess of states can be claimed. On the other hand, missing states in *e.g.* the strange and ϕ sectors make definite conclusions on the confining force even more difficult.

1.1.5. Charmed mesons

Especially the scalar $\boldsymbol{D_{s0}^*(2317)}$ but also the axial-vector $\boldsymbol{D_{s1}(2460)}$ come out too heavy in the GI model (also see below). For the rest, not too many quark-model states have been observed so far, which hardly allows any feedback concerning the confining potential.

1.1.6. Charmonium

In recent years, the PDG listings have been invaded by a plague of charmonium-like, so-called "X" states, several of which may not be resonances at all, but rather threshold [5] or depletion [6] effects (see *e.g.* $\boldsymbol{X(4260)}$ [6] below). Moreover, genuine charmonium states like $\boldsymbol{X(3872)}$

may be shifted considerably [9], turning a correct assignment into a much more difficult task than simply checking the mass predictions of one's favourite quenched quark model. As for the "regular" charmonium spectrum, too many spectroscopic states have evaded observation so far to allow a better understanding of confinement. On the other hand, clear indications of highly excited radial vector states [2] have been systematically ignored by other model builders and the experimental groups themselves.

1.1.7. Bottom mesons

Here, the scarcity of observed [1] excited states strongly hampers any significant contribution to meson spectroscopy.

1.1.8. Bottomonium

As for bottomonium, a correct spectroscopic assignment of $\boldsymbol{\Upsilon(10580)}$, $\boldsymbol{\Upsilon(10860)}$, and $\boldsymbol{\Upsilon(11020)}$ [1] is crucial to understand the interplay of confinement and coupled channels above the open-bottom threshold. The usual interpretation of these states as $\Upsilon(4S)$, $\Upsilon(5S)$, and $\Upsilon(6S)$, respectively, suffers from serious problems (see Ref. [2] and references therein). Also, future experiments at LHC must certainly improve [14] on the resolution achieved in Ref. [15] for any real advancement in spectroscopy.

2. Non-resonant charmonium enhancement $\boldsymbol{X(4260)}$

The $\boldsymbol{X(4260)}$ vector charmonium enhancement [1], discovered [16] in $\pi^+\pi^- J/\psi$ data, is puzzling because of its awkward mass and the non-observation of open-charm decay channels. This has led to various exotic or

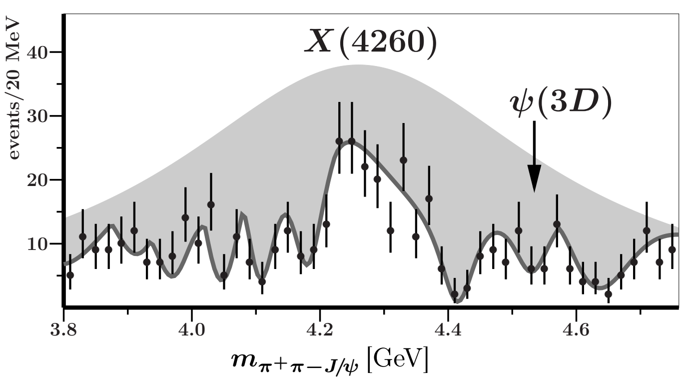

Fig. 1. Non-resonant $\boldsymbol{X(4260)}$ modelled as a very broad structure (shaded area) depleted by $c\bar{c}$ resonances and open-charm thresholds. Effect of new charmonium state $\psi(3D)$ is clearly visible. Data are from Ref. [16]; also see Refs. [6, 17].

molecular model explanations (see Ref. [6] for some references). However, the $\boldsymbol{X(4260)}$ data also display a conspicuous dip precisely at the mass of the established $\boldsymbol{\psi(4415)}$, as well as the absence of peaks corresponding to other known $c\bar{c}$ states. These usually ignored, yet very peculiar features can be understood by assuming [6] a very broad, $\boldsymbol{\sigma}$-like, $\pi^+\pi^-$ distribution centred around 4.26 GeV, but depleted at the energies of $c\bar{c}$ resonances, including a new $\psi(3D)$ state at about 4.53 GeV, as well as open-charm threshold openings (see Fig. 1). Thus, dominant, OZI-allowed processes reveal themselves as a kind of "mirror images" in the — OZI-suppressed — $\pi^+\pi^- J/\psi$ data. For further details, see Ref. [6].

3. $\boldsymbol{X(3872)}$ as a unitarised 1^{++} $c\bar{c}$ state

The $\boldsymbol{X(3872)}$ charmonium-like state was discovered [18] as a $\pi^+\pi^- J/\psi$ enhancement in the decay $B^\pm \to K^\pm\pi^+\pi^- J/\psi$, and later also observed in the hadronic channels $\rho^0 J/\psi$, $\omega J/\psi$, $D^0\bar{D}^0\pi^0$, and $D^0\bar{D}^{*0}$ [1]. The low mass of $\boldsymbol{X(3872)}$ and its remarkable proximity to the D^0D^{*0} threshold has given rise to many exotic or molecular interpretations (see Ref. [9] for some references). However, we have shown [9] that $\boldsymbol{X(3872)}$ is perfectly compatible with a unitarised $2\,{}^3P_1$ $c\bar{c}$ state, but strongly mass-shifted and with a large D^0D^{*0} component in the wave function [19]. Figure 2 displays the $\boldsymbol{X(3872)}$ pole trajectory near the D^0D^{*0} threshold, as well as a comparison of predicted amplitudes with data. For more information, see Refs. [9, 19].

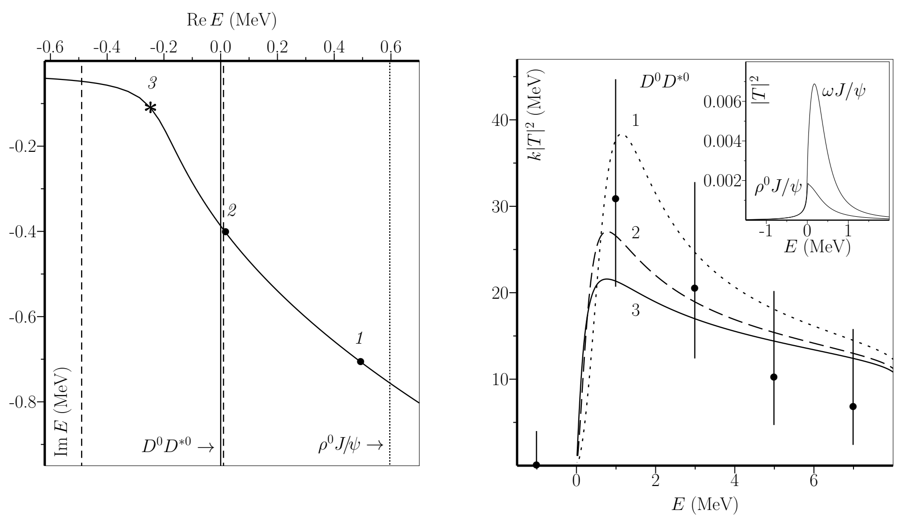

Fig. 2. Left: $\boldsymbol{X(3872)}$ pole trajectory as a function of overall coupling λ; dashed lines delimit allowed [1] pole range. Right: D^0D^{*0} amplitude with data [18]; inset: relative comparison of $\rho^0 J/\psi$ and $\omega J/\psi$ amplitudes. Also see Refs. [9, 17].

4. Understanding the axial-vector charmed mesons

One of the major puzzles in open-charm spectroscopy is the approximate mass degeneracy of the axial-vector (AV) charmed resonances $\boldsymbol{D_1(2420)}$ and $D_1(2430)$, with the former being relatively narrow (20–25 MeV) and the latter very broad ($\sim$ 400 MeV). On the other hand, the AV charmed-strange mesons $\boldsymbol{D_{s1}(2536)}$ and $\boldsymbol{D_{s1}(2460)}$ lie 76 MeV apart, whereas their widths are both very small (0–3 MeV). We have recently explained [10] this odd pattern of masses and widths by coupling the various bare AV charmed states to their dominant decay channels. Unquenching then not only moves the poles where they belong in the complex energy plane (see Fig. 3), but even generates the dynamical mixing of $^3P_1$ and $^1P_1$ components required to describe the data. See further Ref. [10].

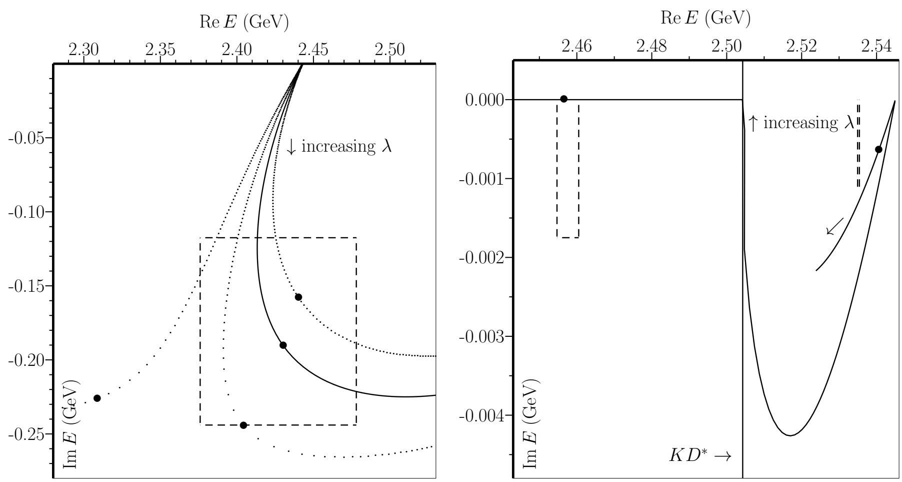

Fig. 3. Left: pole trajectories of $D_1(2430)$ as a function of coupling λ, for different radii r_0; right: trajectories of $\boldsymbol{D_{s1}(2460)}$ and $\boldsymbol{D_{s1}(2536)}$, as a function of λ, for $r_0 = 3.12\,\text{GeV}^{-1}$. Left and right: dashed box, rectangle, and strip delimit experimental [1] $D_1(2430)$, $\boldsymbol{D_{s1}(2460)}$ resp. $\boldsymbol{D_{s1}(2536)}$ pole; see Refs. [10, 17].

5. Conclusions

Meson spectroscopy has progressed only marginally over the past decade when judged on the obtained feedback concerning the confinement and decay mechanisms in QCD, despite the observation of many new and exciting resonances. Blame is to be put on both theorists and experimentalists, on the former ones because of their obsession with the funnel potential and exotics, and on the latter for failing to produce data with much higher resolution and carry out more systematic studies, especially partial-wave analyses [11], in various sectors of the meson spectrum. The clear evidence of large effects from unquenching, as *e.g.* the mass shifts of $\boldsymbol{D^*_{s0}(2317)}$ [3] and $\boldsymbol{X(3872)}$ [9], the dynamically generated light scalar nonet [1, 4], or more generally, due to threshold openings [5], should finally convince people that modern meson spectroscopy must go beyond the traditional quenched approaches like the GI [7] model, no matter how pioneering the latter work was 27 years ago.

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