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NO SERIOUS MESON SPECTROSCOPY WITHOUT SCATTERING*

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The main goal of meson spectroscopy is to understand the confining force, assumed to be based on low-energy QCD. The usual quark models ignore the dynamical effects of $q\bar{q}$ creation and decay. Very recent lattice calculations confirm much earlier model results showing that neglecting such effects, in the so-called quenched approximation, may give rise to large discrepancies, and so distort the meson spectra resulting from quark confinement only. Models that attempt to mimic unquenching by redefining the constituent quark mass or screening the confining potential at large r cannot account for the highly non-perturbative effects on mesonic bound-state and resonance poles, as demonstrated with some published examples.

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1. Introduction

The experimentally observed spectra of mesons and baryons should provide detailed information on quark confinement and other interquark forces, which are believed to result from QCD at low energies. Thus, over the past four decades, work on quark models has attempted to reproduce these spectra by employing confining potentials, which are usually of a Coulomb-plus-linear or "funnel" type, on the basis of short-distance perturbative QCD and long-distance QCD speculations. A typical and often cited example is

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the relativised quark model of Godfrey and Isgur [1]. In such approaches, it is generally assumed that hadronic decay can be treated *a posteriori* and perturbatively, with no appreciable influence on the spectrum itself.

However, very recent unquenched lattice calculations have shown the sizable effects of accounting for dynamical quarks and allowing hadrons to decay strongly. In particular, in Ref. [2] a lattice computation of P-wave $K\pi$ phase shifts and the lowest strange vector-meson resonances was carried out, confirming $K^*(892)$ and tentatively also $K^*(1410)$, though the latter resonance came out about 80 MeV below the experimental [3] mass. More surprisingly, an equally unquenched calculation by the same lattice collaboration [4], yet without two-meson correlators and so no hadronic decay, predicted a (bound) $K^*(1410)$ state roughly 300 MeV higher in mass. Despite possible inaccuracies due to problems in dealing with inelastic resonances and very light quarks/pions on the lattice, this enormous difference confirms the importance of including strong decay for reliable predictions in meson spectroscopy. Moreover, in another study by still the same lattice group, the low mass of the charmed-strange $D^*_{s0}(2317)$ meson was reproduced by including two-meson correlators corresponding to the subthreshold S-wave DK channel [5], in agreement with an unquenched quark-model description a decade earlier [6] (also see below).

As already said, lattice QCD still faces considerable problems in dealing with resonances that have multiple decay modes and in extrapolating predictions towards the physical pion mass, besides serious difficulties in dealing with heavy quarkonia and excited states. Therefore, in the foreseeable future, QCD-inspired quark models will still be of a crucial importance in interpreting and advising on experiments in hadron spectroscopy. Clearly, such models should go beyond the quenched approximation of the confinement-only approaches mentioned above.

One attempt to do this in a "cheap" way amounted to estimating hadron-loop mass corrections in charmonium [7], and suggesting that, to a large extent, it might suffice to adjust the charm quark mass. However, this is most likely a too simplistic assessment, since the size of hadronic loop corrections will depend on the wave function of a specific state, in particular its nodal structure, in view of the peaked shape of the string-breaking interaction leading to decay, as confirmed on the lattice [8]. Furthermore, above the lowest decay threshold, the effects will be governed by S-matrix unitarity and analyticity, which are generally non-perturbative and non-linear (see the examples below), except for unphysically small couplings [9].

Another approach to mimicking unquenching in quark models is by screening the confining potential at larger interquark separations, making it, in fact, non-confining and so allowing for decay. However, such decays are pathological, as they lead to free quarks and not hadrons in the final state. Of course, one can adjust the model parameters such that the thresholds for decay into free quarks lie above all experimentally observed states. However, then one would purport to describe physical resonances by treating them as stable hadrons, ignoring effects due to S-matrix analyticity and genuine decay thresholds. Moreover, the usually employed screened potentials in quark models are, for short distances, similar to the funnel potential [1], as *e.g.* in the model of Ref. [10], which on top of that has interquark meson exchanges. Thus, these models share some of the shortcomings [11] of the Godfrey–Isgur model [1], such as much too large radial separations for the lowest states in the light-quark sector.

In this paper, we shall make the case for an S-matrix approach to meson spectroscopy, as the only reliable phenomenological way to unquench the quark model, describing both mesonic bound states and resonances in a unique analytic formalism, with meson-loop effects included to all orders. For that purpose, published work on several enigmatic meson resonances will be briefly reviewed. The organisation is as follows: Sec. 2 deals with the original model and the vector charmonium spectrum, Sec. 3 with the light scalar mesons, Sec. 4 with the charmed scalars $D_{s0}^*(2317)$ and $D_0^*(2300)$, Sec. 5 with the axial-vector charmonium state $X(3872)$, and Sec. 6 with the $J^P = 1^+$ open-charm mesons $D_{s1}(2536)$, $D_{s1}(2460)$, $D_1(2420)$, and $D_1(2430)$. A few conclusions are presented in Sec. 7.

2. HO model and vector charmonium spectrum

The first three vector charmonium levels, discovered almost four decades ago, seem to suggest a confining potential with decreasing splittings for increasing radial quantum number. Such a pattern can result from a power-law potential r^n with $n < 2$. The simplest case is a linear potential, but also a funnel-type potential, which includes a Coulombic piece, will do, as *e.g.* in the model by Godfrey and Isgur [1]. However, the coupled-channel model of Ref. [12], employing an HO potential with constant frequency and a transition potential mimicking string breaking at a certain distance to describe OZI-allowed strong decay, leads to a similar result. Namely, an equidistant HO spectrum, with degenerate S and D states, is transformed into the physical charmonium spectrum by unquenching (see Fig. 1 in Ref. [12]). Moreover, even the first few $b\bar{b}$ states are automatically reproduced [12].

3. $f_0(500)$ and other light scalar mesons

An extended version of the above unquenched HO model [12], with a smeared-out transition potential and relativistic kinematics in the open decay channels, was applied to heavy and light vector and pseudoscalar mesons [13]. This very same model was then used, with unchanged parameters, to study scalar mesons made of light quarks [14]. The resulting S-matrices revealed resonance poles not only in the expected 1.3–1.5 GeV energy region, but also well below 1 GeV. It comprised a complete extra scalar nonet, including the then still very controversial $f_0(500)$ ("σ") and $K_0^*(800)$ ("κ") mesons, with pole positions [14] close to present-day world averages [3]. In Fig. 1 the model's parameter-free prediction of S-wave $\pi\pi$ phase shifts is shown with old data.

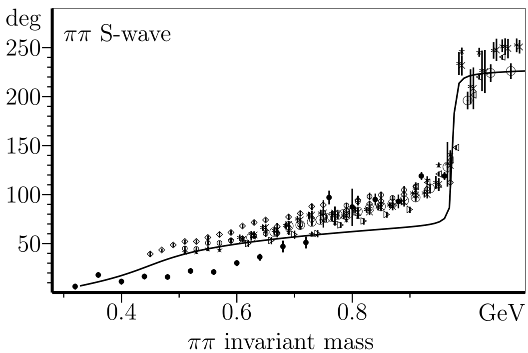

Fig. 1. S-wave $\pi\pi$ phase shift as predicted in Ref. [14] *vs.* data from the 1970s.

4. Charmed scalars $D_{s0}^*(2317)$ and $D_0^*(2300)$

A momentum-space version [15] of the above model [13] was applied [6] to the $D_{s0}^*(2317)$ and $D_0^*(2300)$ [3] charmed scalar mesons, in a very simple approximation for the lowest states, but with quark masses and HO frequency fixed at the values determined in Ref. [13]. This very same model, with identical values for the overall coupling λ and the string-breaking distance r_0, had been used before in an excellent fit [16] to the S-wave $K\pi$

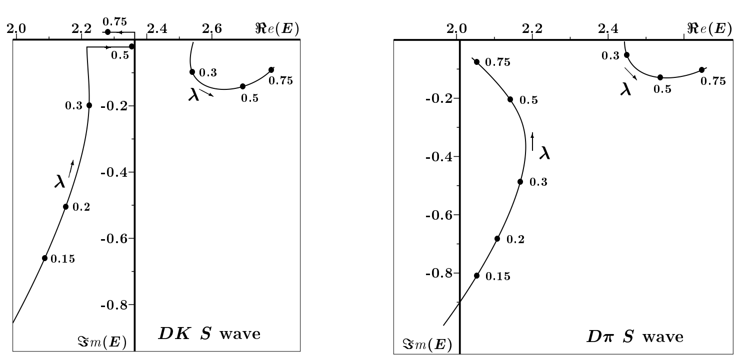

Fig. 2. Pole trajectories of $D_{s0}^*(2317)$ (left) and $D_0^*(2300)$ (right) as a function of λ [6], with $\lambda = 0.75$ the physical value. Higher recurrences are also shown.

phase shifts up to 1.5 GeV, while simultaneously reproducing the $K_0^*(800)$ and $K_0^*(1430)$ [3] resonances. The resulting [6] pole trajectories as a function of λ are shown in Fig. 2, with an excellent prediction for $D_{s0}^*(2317)$.

5. Axial-vector charmonium state $X(3872)$

The $J^{PC} = 1^{++}$ charmonium state $X(3872)$ [3] is a perfect laboratory for quark and effective models, as it is bound by only 0.11 MeV with respect to its lowest OZI-allowed decay channel, *i.e.*, D^0D^{*0}. This system was studied recently in a multichannel momentum-space model and also in a two-component coordinate-space model. The former [17] demonstrated that an $X(3872)$ resonance pole with a realistic imaginary part (see Fig. 1 in Ref. [17]) can result from unquenching a bare $2\,^3P_1$ $c\bar{c}$ state about 100 MeV higher in mass via several two-meson channels, including the OZI-forbidden $\rho^0 J/\psi$ and $\omega J/\psi$ channels, and accounting for the ρ^0, ω widths. On the other hand, the latter paper [18] showed that $X(3872)$ has a sizable $c\bar{c}$ component and thus cannot be considered a D^0D^{*0} molecule (also see Refs. [19] and [20]).

6. 1^+ charmed mesons $D_{s1}(2536)$, $D_{s1}(2460)$, $D_1(2420)$, $D_1(2430)$

The charmed-strange and charmed-light mesons with $J^P = 1^+$ reveal [3] a very irregular pattern of masses and widths, impossible to understand with the usual perturbative spin–orbit interactions and decay amplitudes, or heavy-quark effective theory. However, a multichannel unquenched quark-model calculation with bare $1\,^3P_1$ and $1\,^1P_1$ $c\bar{s}$ or $c\bar{q}$ seeds does an excellent job in reproducing the data [21]. In Fig. 3 some pole trajectories are shown.

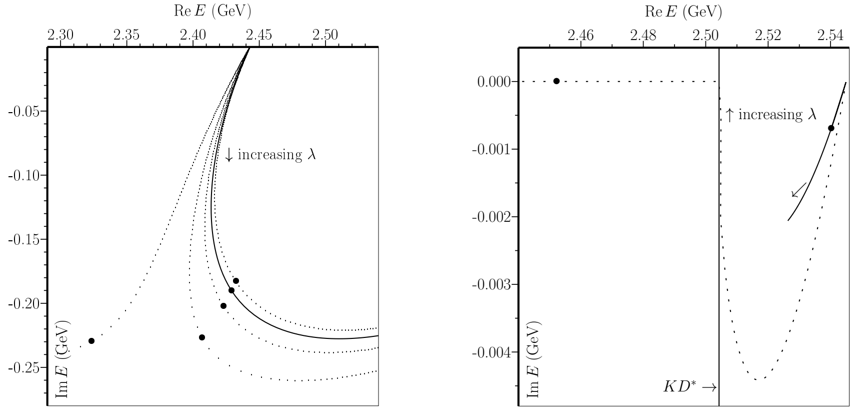

Fig. 3. Pole trajectories of $D_1(2430)$ (left), $D_{s1}(2460)$ (right, dotted) and $D_{s1}(2536)$ (right, solid). For further details, see Ref. [21].

7. Conclusions

Meson spectroscopy is truly different from atomic spectroscopy, in that line widths can be of the same order as level spacings. S-matrix analyticity then implies that real level shifts may be of similar or even greater magnitude. The proper, non-perturbative way to deal with this is by describing mesons as resonances or bound states in a scattering process of the dominant real or virtual decay products, yet while dealing with quark confinement at the same time and on an equal footing. The above examples from various sectors of the meson spectrum should provide support for such an approach. In conclusion, meson spectroscopy is even more involved because of natural, non-resonant threshold enhancements (see Ref. [22]).

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