UNQUENCHING THE MESON SPECTRUM: A MODEL STUDY OF EXITED ρ RESONANCES*

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Quark models taking into account the dynamical effects of hadronic decay often produce very different predictions for mass shifts in the hadron spectrum. The consequences for meson spectroscopy can be dramatic and completely obscure the underlying confining force. Recent unquenched lattice calculations of mesonic resonances that also include meson–meson interpolators provide a touchstone for such models, despite the present limitations in applicability. On the experimental side, the $\rho(770)$ meson and its several observed radial recurrences are a fertile testing ground for both quark models and lattice computations. Here, we apply a unitarised quark model that has been successful in the description of many enigmatic mesons to these vector ρ resonances and the corresponding P-wave $\pi\pi$ phase shifts. This work is in progress, with encouraging preliminary results.

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1. Introduction

The static quark model, which describes hadrons as pure bound states of confined quarks and antiquarks, has remained largely unchallenged for about 40 years. Even nowadays, most experimentalists still confront the enhancements in their meson data with the relativised quark model of Godfrey and Isgur (GI) [1] in order to arrive at an assignment or otherwise claim to

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have found evidence of some exotic state. Now, the GI model is indeed the most comprehensive calculation of practically all possible quark–antiquark masses, employing the usual Coulomb-plus-linear ("funnel") confining potential. However, the insistence on comparing both narrow and broad structures in cross sections directly with the infinitely sharp levels of a manifestly discrete confinement spectrum is clearly a poor-man's approach. Yet, models going beyond the static quark model have been around for almost the same four decades, the pioneering ones being the Cornell model for charmonium [2], the Helsinki model for light pseudoscalars and vectors [3, 4], and the Nijmegen model for heavy quarkonia [5] and all pseudoscalar and vector mesons [6]. Despite the at times huge mass shifts predicted by these models, for many years the effects of decay, also called coupled-channel contributions or unitarisation, were largely ignored. Instead, inspired by perturbative QCD, hadron spectroscopists made their models more and more sophisticated at the level of the confining potential, with *e.g.* spin-orbit splittings and also relativistic corrections [1], which are nevertheless quite insignificant as compared to many of the large mass shifts from unitarisation.

Only since the observation of a growing number of enigmatic mesons, whose masses or observed decays do not seem to fit in the GI and similar static quark models, more authors have started to take into account dynamical effects from strong decay and scattering. Parallelly, very recent unquenched lattice computations have shown remarkably large mass shifts due to the inclusion of two-meson interpolators besides the usual quark–antiquark ones, thus confirming the importance of decay for meson spectroscopy.

An appropriate class of mesons to study these issues is $\rho(770)$ and its several radial excitations, together with the corresponding P-wave $\pi\pi$ phase shifts, because of the considerable amount of available data, despite being mostly old [7]. Here, we shall present preliminary results in the context of the Resonance-Spectrum Expansion (RSE), which is a momentum-space variant of the unitarised model employed in Ref. [5].

In Sec. 2, meson mass shifts in different quark models that include hadronic decay are compared, also with a recent lattice calculation. Section 3 is devoted to a very brief description of the RSE model as applied to the isovector vector mesons, with some preliminary yet encouraging results. A few conclusions are drawn in Sec. 4.

2. Mass shifts from "unquenching" in models and on the lattice

Quark models that dynamically account for decay are often called "unquenched" [8–12]. Now, this is actually a very sloppy name, as the term "unquenched" originates in lattice calculations with dynamical instead of static quarks, via a fermion determinant. We shall nevertheless use this inaccurate name when referring to such quark models, because the various approaches are very different. For instance, Refs. [9] and [11] evaluate real or complex mass shifts from the lowest-order hadronic loops, Ref. [10] constructs and uses a screened confining potential supposedly resulting from quark loops, while Ref. [12] includes meson loops to all orders in a fully unitary S-matrix formalism. Also the original models of Refs. [2, 5, 6] were truly unitarised. But there are enormous differences as well in the computed mass shifts from unquenching, even among, in principle, similar models. In Table I, we show

TABLE I

Negative mass shifts from unquenching. Abbreviations: BT = bootstrap, χ = chiral, QM = quark model, RGM = Resonating Group Method, RSE = Resonance Spectrum Expansion, CC = coupled channels, HO = harmonic oscillator, WF = wave function, PT = perturbation theory, q = light quark; P, V, S = pseudoscalar, vector, scalar meson, respectively.

Refs.	Approach	Mesons	$-\Delta M$ [MeV]
[2]	S-matrix, r-space	charmonium	48–180
[3, 4]	one-loop BT	light P, V	530–780, 320–500
[5, 6]	S-matrix, r-space	$q\bar{q}$, $c\bar{q}$, $c\bar{s}$, $c\bar{c}$, $b\bar{b}$; P, V	$\approx$ 30–350
[13]	S-matrix, r-space	light, intermediate S	510–830, ~ 0
[14]	χ QM, RGM	$\rho(770)$, $\phi(1020)$	328, 94
[15]	RSE, p-space	$D^\star_{s0}(2317)$, $D^\star_0(2400)$	260, 410
[16]	CC, χ Lagrangian	$D^\star_{s0}(2317)$, $D^\star_s(2632)$	173, 51
[17]	CC, HO WF	charmonium	165–228
[18]	CC, PT	charmonium	416–521
[19]	RSE, p-space	$X(3872)$	$\approx$ 100
[20]	RSE, p-space	$c\bar{q}$, $c\bar{s}$; $J^P = 1^+$	4–13, 5–93

the corresponding predictions of a number of unquenched quark models for mesons. Note that the mass shifts in Refs. [5, 6, 13, 15, 19, 20] are, in general, complex, in some cases [13, 15, 20] with huge imaginary parts, corresponding to pole positions in an exactly solved S-matrix. As for the disparate shifts among the various approaches, they are due to differences in the assumed decay mechanism, included channels, and possibly drastic approximations. Another crucial point should be to properly account for the nodal structure of the bare $q\bar{q}$ wave functions.

Faced with these discrepancies, one is led to look at unitarised lattice results, preferably on $\rho(770)$ and its radial recurrences, which we will study here with the RSE formalism. Unfortunately, no such calculations have been published so far. Nevertheless, a recent paper [21] on the related vector meson $K^\star(892)$ and the associated P-wave $K\pi$ phase shifts provides very useful information. Not only were the $K^\star$ mass and extrapolated width reasonably well reproduced, but also a prediction, albeit approximate, was made for the first radial excitation $K^\star(1410)$ [7], finding a mass of 1.33 ± 0.02 GeV. Now, the main surprise about the latter number is not so much its relative closeness to the experimental value and the 250-MeV gap with *e.g.* the "quenched" GI [1] prediction. Rather, being about 300 MeV lower than the value found by the same lattice group in another unquenched calculation [22] yet with no two-meson interpolators included, it showcases the potentially dramatic effects of unitarisation on meson spectra. This is an excellent incentive to study the ρ spectrum and P-wave $\pi\pi$ phases in detail.

3. RSE modelling of ρ recurrences and P-wave $\pi\pi$ scattering

The experimental status of radial ρ excitations was reviewed minutely in Ref. [23]. Suffice it here to stress the clearly biased handling of a frequently reported $\rho(1250)$ resonance by the Particle Data Group (PDG), by lumping some of its observations under $\rho(1450)$ [7], instead of creating a separate entry in the meson listings. The PDG also bluntly omits a reference to a relatively recent phase-shift analysis [24] that concludes $\rho(1250)$ to be the most important ρ excitation in order to fit the data. Moreover, there is the well-established excited $s\bar{q}$ resonance $K^\star(1410)$ (see PDG [7] summary table), now also confirmed on the lattice [21]. This lends further evidence to the existence of $\rho(1250)$, as predicted long ago in the model of Ref. [6].

The general expressions for the RSE off-energy-shell $\mathcal{T}$-matrix and corresponding on-shell $\mathcal{S}$-matrix have been given in several papers (see *e.g.* Ref. [20]). In the present case of P-wave $\pi\pi$ scattering, the quantum numbers of the system are $I^G J^{PC} = 1^+ 1^{--}$, which couples to the $I=1$ quark–antiquark state $(u\bar{u} - d\bar{d})/\sqrt{2}$ in the spectroscopic channels $^3S_1$ and $^3D_1$. In the meson–meson sector, we only consider channels allowed by total angular momentum J, isospin I, parity P, and when possible G-parity G. The included combinations from the lowest-lying meson nonets [7] are: PP, VP, VV, VS, AP, and AV, where P stands for $J^{PC} = 0^{-(+)}$, V for $1^{-(-)}$, S for $0^{+(+)}$, and A for $1^{+(+)}$ or $1^{+(-)}$. This choice of meson–meson channels is motivated by the observed two- and multi-particle decays of the ρ recurrences up to $\rho(1900)$ [7], which include several intermediate states containing resonances from the referred nonets. For instance, the PDG lists [7] under the 4π decays of $\rho(1450)$ the modes $\omega\pi$, $a_1(1260)\pi$, $h_1(1170)\pi$, $\pi(1300)\pi$, $\rho\rho$, and $\rho(\pi\pi)_{S\text{-wave}}$, where $(\pi\pi)_{S\text{-wave}}$ is probably dominated by the $f_0(500)$ [7] scalar resonance. By the same token, the 6π decays of $\rho(1900)$ will most likely include important contributions from modes as $b_1(1235)\rho$, $a_1(1260)\omega$, *etc.* For consistency of our calculation, we generally include complete nonets in the allowed decays, and not just individual modes observed in experiment. The only exception is the important $\pi(1300)\pi$ P′P mode, because no complete nonet of radially excited pseudoscalar mesons has been observed so far [7]. The resulting 26 channels are given in Table II.

TABLE II

Included classes of decay channels. Short-hand: $\sigma = f_0(500)$, $a_0 = a_0(980)$, $\kappa = K_0^\star(800)$, $a_1 = a_1(1260)$, $b_1 = b_1(1235)$, $h_1 = h_1(1170)$, $K_1 = K_1(1270)$, $\tilde{K}_1 = K_1(1400)$, $f_1 = f_1(1285)$, $\pi' = \pi(1300)$ [7].

Nonets	Two-meson channels	L
PP	$\pi\pi$, KK	1
VP	$\omega\pi$, $\rho\eta$, $\rho\eta'$, $K^\star K$	1
VV	$\rho\rho$, $K^\star K^\star$	1
VS	$\rho\sigma$, ωa_0, $K^\star\kappa$	$0, 2$
AP	$a_1\pi$, $b_1\eta$, $b_1\eta'$, $h_1\pi$, K_1K, $\tilde{K}_1K$	0
AV	$a_1\omega$, $b_1\rho$, $f_1\rho$, $K_1K^\star$, $\tilde{K}_1K^\star$	0
P′P	$\pi'\pi$	1

With the few available parameters [23], a good fit to the P-wave phase shifts is only possible up to about 1.2 GeV, whereabove the phases rise a bit too fast, though their qualitative behaviour can be reproduced. Improvements may require more flexibility in the transition potential, by allowing different decay radii for the various classes of two-meson channels, and/or allowing for complex-mass resonances in the final states [23]. The present fit yields a reasonable $\rho(770)$ pole, *viz.* at $(754 - i67)$ MeV, while there are two poles in the range of 1.2–1.5 GeV, compatible with both $\rho(1250)$ and $\rho(1450)$.

4. Conclusions

Meson spectroscopists are slowly starting to leave the stone-age behind, by realising that effects from strong decay can be of the same order as the bare $q\bar{q}$ level splittings themselves. Enormous obstacles lie on the road ahead, demanding more theoretical work, improved lattice calculations, and much better experimental analyses. The excited ρ spectrum provides an excellent laboratory for such efforts. To make life even harder, several bumps in meson production processes [25] may just be non-resonant threshold enhancements (see [26]).

REFERENCES

[1] S. Godfrey, N. Isgur, *Phys. Rev. D* **32**, 189 (1985).

[2] E. Eichten *et al.*, *Phys. Rev. D* **17**, 3090 (1978) [*Erratum ibid.* **22**, 787 (1980)]; *Phys. Rev. D* **21**, 203 (1980).

[3] N.A. Tornqvist, *Ann. Phys.* **123**, 1 (1979).

[4] M. Roos, N. Tornqvist, *Z. Phys. C* **5**, 205 (1980).

[5] E. van Beveren, C. Dullemond, G. Rupp, *Phys. Rev. D* **21**, 772 (1980).

[6] E. van Beveren, G. Rupp, T.A. Rijken, C. Dullemond, *Phys. Rev. D* **27**, 1527 (1983).

[7] K.A. Olive *et al.* [PDG Collaboration], *Chin. Phys. C* **38**, 090001 (2014).

[8] E.S. Swanson, *J. Phys. G* **31**, 845 (2005) [`arXiv:hep-ph/0504097`].

[9] R. Bijker, E. Santopinto, *AIP Conf. Proc.* **947**, 168 (2007).

[10] P. Gonzalez, *Int. J. Mod. Phys. Conf. Ser.* **02**, 178 (2011).

[11] T.J. Burns, *Phys. Rev. D* **90**, 034009 (2014) [`arXiv:1403.7538 [hep-ph]`].

[12] M. Cardoso, G. Rupp, E. van Beveren, *Eur. Phys. J. C* **75**, 26 (2015) [`arXiv:1411.1654 [hep-ph]`].

[13] E. van Beveren *et al.*, *Z. Phys. C* **30**, 615 (1986) [`arXiv:0710.4067 [hep-ph]`].

[14] P.J. d. A. Bicudo, J.E.F.T. Ribeiro, *Phys. Rev. D* **42**, 1635 (1990).

[15] E. van Beveren, G. Rupp, *Phys. Rev. Lett.* **91**, 012003 (2003) [`arXiv:hep-ph/0305035`].

[16] Y.A. Simonov, J.A. Tjon, *Phys. Rev. D* **70**, 114013 (2004) [`arXiv:hep-ph/0409361`].

[17] Y.S. Kalashnikova, *Phys. Rev. D* **72**, 034010 (2005) [`arXiv:hep-ph/0506270`].

[18] T. Barnes, E.S. Swanson, *Phys. Rev. C* **77**, 055206 (2008).

[19] S. Coito, G. Rupp, E. van Beveren, *Eur. Phys. J. C* **71**, 1762 (2011) [`arXiv:1008.5100 [hep-ph]`].

[20] S. Coito, G. Rupp, E. van Beveren, *Phys. Rev. D* **84**, 094020 (2011) [`arXiv:1106.2760 [hep-ph]`].

[21] S. Prelovsek, L. Leskovec, C.B. Lang, D. Mohler, *Phys. Rev. D* **88**, 054508 (2013).

[22] G.P. Engel, C.B. Lang, D. Mohler, A. Schäfer, *PoS* **Hadron2013**, 118 (2013) [`arXiv:1311.6579 [hep-ph]`].

[23] S. Coito, G. Rupp, E. van Beveren, *Bled Workshops Phys.* **16**, 30 (2015) [`arXiv:1510.00938 [hep-ph]`].

[24] Y.S. Surovtsev, P. Bydzovsky, *Nucl. Phys. A* **807**, 145 (2008).

[25] E. van Beveren, G. Rupp, *Ann. Phys.* **323**, 1215 (2008) [`arXiv:0706.4119 [hep-ph]`].

[26] E. van Beveren, G. Rupp, S. Coito, *Acta Phys. Pol. B Proc. Suppl.* **9**, 583 (2016) [`arXiv:1605.03437 [hep-ph]`], this issue.