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THE $f_0(1790)$ AND $a_0(1950)$ RESONANCES AS EXCITED $\bar{q}q$ STATES IN THE EXTENDED LINEAR SIGMA MODEL*

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A decade ago, the BES Collaboration reported the discovery of a new scalar isosinglet resonance denoted as $f_0(1790)$. The finding was subsequently confirmed by the LHCb. Recently, the existence of the corresponding isotriplet state — the $a_0(1950)$ resonance — has been claimed by the BaBar Collaboration. We investigate whether these resonances can be described as excited $\bar{q}q$ states. To this end, a comprehensive Lagrangian containing ground-state $\bar{q}q$ mesons as well as their first excitations is constructed in accordance with symmetries of the strong interaction. Both $f_0(1790)$ and $a_0(1950)$ emerge as compatible with $\bar{q}q$ excitations; however, tension appears to arise between the simultaneous interpretation of $f_0(1790)/a_0(1950)$ and pseudoscalar mesons $\eta(1295)$, $\pi(1300)$, $\eta(1440)$ and $K(1460)$ as excited $\bar{q}q$ states.

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1. Introduction

Strong interaction exhibits an abundantly populated spectrum of hadrons. Historical as well as current experimental data indicate the necessity to introduce various quantum numbers for these states — most notably isospin I,

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total spin J, parity P and charge conjugation C. Mesons are hadrons with integer spin. According to the Particle Data Group [1], their number is particularly large in the scalar ($J^P = 0^+$) channel where the following resonances are listed in the energy region up to approximately 2 GeV:

$$\begin{array}{lllll} f_0(500)/\sigma\,, & K_0^\star(800)/\kappa\,, & a_0(980)\,, & f_0(980)\,, & f_0(1370)\,, \\ K_0^\star(1430)\,, & a_0(1450)\,, & f_0(1500)\,, & f_0(1710)\,, & K_0^\star(1950)\,, \\ a_0(1950)\,, & f_0(2020)\,, & f_0(2100)\,. & & \end{array} \tag{1}$$

The abundance is only marginally smaller in the pseudoscalar ($J^P = 0^-$) channel and the same energy region

$$\begin{array}{llllllll} \pi\,, & K\,, & \eta\,, & \eta'(958)\,, & \eta(1295)\,, & \pi(1300)\,, & \eta(1405)\,, & K(1460)\,, \\ \eta(1475)\,, & \eta(1760)\,, & \pi(1800)\,, & K(1830)\,. & & & & \end{array}$$

Masses and decay properties of these states are obviously correlated with their structure; features of the hadron spectrum can, as a matter of principle, be explained by the theory of strong interaction — Quantum Chromodynamics (QCD). The non-perturbativity of QCD precisely in the energy region where hadrons appear [2] has brought about the emergence of the famous Quark Model and its refined versions (see, *e.g.*, Ref. [3]). In this approach, states are composed of the constituent quarks — those emerging from the perturbative quarks of QCD by means of strong dynamics (see, *e.g.*, Ref. [4]). For the states listed above, the expectation due to their decay patterns is that they are composed of u, d and s constituent quarks.

The large number of these states implies that not all of them can be explained as having the $\bar{q}q$ (quarkonium) structure — the spectrum may also contain tetraquark [5] or glueball states [6]. However, the existence of states with exactly the same quantum number but different masses [η, $\eta'(958)$, $\eta(1295)$, $\ldots$; π, $\pi(1300)$, $\ldots$; f_0 states; $\ldots$] leads to the intriguing possibility that, in addition to ground-state quarkonia, the meson spectrum may also contain their radial excitations. Here, we explore this further.

Studies of excited states (that started already several decades ago [7]) are important for various reasons, for example, since the chiral symmetry has been suggested to become effectively restored in excited mesons [8] and since new experimental candidate states have emerged in the last decade. The observation of the $IJ^P = 00^+$ $f_0(1790)$ resonance by the BES and LHCb collaborations [9, 10] is of particular importance. The data suggest the resonance to predominantly couple to pions. The same is also true for lower-lying resonances [$f_0(500)$, $f_0(1370)$, $f_0(1500)$] where the ground-state quarkonium is expected. Hence, it appears warranted to explore whether $f_0(1790)$ can represent an excited $\bar{q}q$ state.

Recently, the BaBar Collaboration [11] has reported the observation of the $IJ^P = 10^+$ $a_0(1950)$ resonance; since the ground-state quarkonium is expected to contribute to the lower-lying $a_0(980)$ and $a_0(1450)$ states, it appears again warranted to suggest that $a_0(1950)$ represents a $\bar{q}q$ excitation. We explore these hypotheses by means of the Extended Linear Sigma Model (eLSM).

2. Model and implications

The Extended Linear Sigma Model is an effective approach to QCD: its degrees of freedom are not quarks and gluons but rather hadrons. It implements symmetries of QCD as well as their breaking and it contains degrees of freedom equal to those observed in experiment. If isospin multiplets are considered single degrees of freedom, there are 16 $\bar{q}q$ ground states and 8 $\bar{q}q$ excited states plus the scalar glueball in the model. Hence, it is expected to entail important aspects of the strong interaction.

The model has already been used extensively to study $\bar{q}q$ and glueball dynamics in vacuum [12]. The general form of its Lagrangian is $\mathcal{L} = \mathcal{L}_{\rm dil} + \mathcal{L}_0 + \mathcal{L}_E$ where the terms on the right-hand side respectively denote the dilaton (glueball), ground-state $\bar{q}q$ and excited $\bar{q}q$ contributions. $\mathcal{L}_{\rm dil}$ and $\mathcal{L}_0$ are discussed in depth in Ref. [12]. A detailed discussion of the excited-state Lagrangian is presented in Ref. [13]; an abbreviated version is presented in the following.

The excited-state Lagrangian $\mathcal{L}_E$ has the following structure [13]:

$$\begin{aligned}\mathcal{L}_E = {} & \mathrm{Tr}\left[(D_\mu \Phi_E)^\dagger (D_\mu \Phi_E)\right] - (m_0^*)^2\,\mathrm{Tr}\left(\Phi_E^\dagger \Phi_E\right) \\ & + \mathrm{Tr}\left(\Phi_E^\dagger \Phi_E E_1 + \Phi_E \Phi_E^\dagger E_1\right) \\ & -\lambda_2^*\,\mathrm{Tr}\left(\Phi_E^\dagger \Phi_E \Phi^\dagger \Phi + \Phi_E \Phi_E^\dagger \Phi \Phi^\dagger\right) - \xi_2\,\mathrm{Tr}\left(\Phi_E^\dagger \Phi \Phi_E^\dagger \Phi + \Phi^\dagger \Phi_E \Phi^\dagger \Phi_E\right) \\ & +h_2^*\,\mathrm{Tr}\left(\Phi_E^\dagger L_\mu L^\mu \Phi + \Phi^\dagger L_\mu L^\mu \Phi_E + R_\mu \Phi_E^\dagger \Phi R^\mu + R_\mu \Phi^\dagger \Phi_E R^\mu\right) \\ & +2h_3^*\,\mathrm{Tr}\left(L_\mu \Phi_E R^\mu \Phi^\dagger + L_\mu \Phi R^\mu \Phi_E^\dagger\right) - \kappa_2\left[\mathrm{Tr}\left(\Phi_E^\dagger \Phi + \Phi^\dagger \Phi_E\right)\right]^2 . \quad (2)\end{aligned}$$

It is constructed under the conditions that (*i*) the chiral and dilatation symmetries (and the breaking mechanism as appropriate) are considered; (*ii*) terms that lead to mixing of Lagrangian states or terms suppressed in the limit of large number of colours ($N_{\rm c}$) are neglected[1] and (*iii*) only terms that turn out to lead to kinematically allowed decays are included.

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[1] The only exception to this condition is the κ_2 term that is necessary to induce the mass splitting of $f_0(1790)$ and $a_0(1950)$, see also the discussion below.

In Eq. (2), Φ_E is the multiplet containing excited $\bar{q}q$ states. For three flavours it reads $\Phi_E = \sum_{i=0}^{8}(S_i^E + iP_i^E)T_i$, where $T_i\,(i = 0,\ldots,8)$ denote the generators of U(3), while S_i^E and P_i^E are, respectively, the scalar and pseudoscalar fields. Then we have

$$\Phi_E = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{(\sigma_{\mathrm{N}}^E + a_0^{0E}) + i(\eta_{\mathrm{N}}^E + \pi^{0E})}{\sqrt{2}} & a_0^{+E} + i\pi^{+E} & K_0^{\star+E} + iK^{+E} \\ a_0^{-E} + i\pi^{-E} & \frac{(\sigma_{\mathrm{N}}^E - a_0^{0E}) + i(\eta_{\mathrm{N}}^E - \pi^{0E})}{\sqrt{2}} & K_0^{\star 0E} + iK^{0E} \\ K_0^{\star-E} + iK^{-E} & \bar{K}_0^{\star 0E} + i\bar{K}^{0E} & \sigma_S^E + i\eta_{\mathrm{S}}^E \end{pmatrix} . \tag{3}$$

Φ is the multiplet containing ground-state scalars and pseudoscalars. L_μ and R_μ are the multiplets containing ground-state vectors and axial-vectors; the structure of these matrices is analogous to that of Φ_E. Additionally, $D^\mu\Phi_E = \partial^\mu\Phi_E - ig_{E1}(L^\mu\Phi_E - \Phi_E R^\mu)$ is the derivative transforming covariantly under the chiral U(3) × U(3) group. Non-vanishing quark masses induce explicit breaking of the chiral symmetry, modelled here via the Lagrangian term containing $E_1 = \mathrm{diag}\{0, 0, \epsilon_{\mathrm{S}}^E\}$. Note that the spontaneous chiral-symmetry breaking is implemented in the ground-state sector via shifting the non-strange and strange $IJ^P = 00^+$ fields by their respective vacuum expectation values.

In accordance with our hypotheses, the excited non-strange $IJ^P = 00^+$ state σ_{N}^E is assigned to $f_0(1790)$; its isotriplet partner a_0^E is assigned to $a_0(1950)$. The non-strange and strange $IJ^P = 00^-$ states η_{N}^E and η_{S}^E are assigned to the $\eta(1295)$ and $\eta(1440)$ resonances[2]. With this, parameters (or parameter combinations [13]) entering all mass terms can be calculated. Four masses are predicted and all values can be found in Table I.

Current experimental situation allows only the determination of parameters relevant for decays of excited into ground states. Nonetheless, just two parameters — h_2^* and h_3^*, fixed from $\Gamma_{f_0(1790)\to\pi\pi} = (270 \pm 45)$ MeV and $\Gamma_{f_0(1790)\to KK} = (70 \pm 40)$ MeV [9] — lead to a prediction of more than 35 decays for almost all other model states. See Table I for all numbers.

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[2] As discussed in Ref. [13], there is uncertainty whether the energy region ~ 1.4 GeV contains one or two pseudoscalar states: PDG listings [1] contain $\eta(1405)$ and $\eta(1475)$, while only $\eta(1440)$ appears in BES data [14]. Here, $\eta(1440)$ is present but our results would remain virtually unchanged if, alternatively, $\eta(1475)$ data were used.

TABLE I

Masses and decays of the excited $\bar{q}q$ states. Widths marked as "suppressed" depend only on large-N_{c} suppressed parameters that have been set to zero. Masses/widths marked with (*) are used as input; the others are predictions.

Excited state	IJ^P	Mass [MeV]	Decay	Width [MeV]
$f_0(1790)$	00^+	1790 ± 35*	$\sigma_{\mathrm{N}}^E \to \pi\pi$	270 ± 45*
			$\sigma_{\mathrm{N}}^E \to KK$	70 ± 40*
			$\sigma_{\mathrm{N}}^E \to a_1(1260)\pi$	47 ± 8
			$\sigma_{\mathrm{N}}^E \to \eta\eta'$	10 ± 2
			$\sigma_{\mathrm{N}}^E \to \eta\eta$	7 ± 1
			$\sigma_{\mathrm{N}}^E \to f_1(1285)\eta$	1 ± 0
			$\sigma_{\mathrm{N}}^E \to K_1 K$	0
			$\sigma_{\mathrm{N}}^E \to \sigma_{\mathrm{N}}\pi\pi$	0
			Total	405 ± 96
$a_0(1950)$	10^+	1931 ± 26*	$a_0^E \to \eta\pi$	94 ± 16
			$a_0^E \to KK$	94 ± 54
			$a_0^E \to \eta'\pi$	48 ± 8
			$a_0^E \to f_1(1285)\pi$	28 ± 5
			$a_0^E \to K_1 K$	9 ± 5
			$a_0^E \to a_1(1260)\eta$	6 ± 1
			$a_0^E \to a_0(1450)\pi\pi$	1 ± 1
			Total	280 ± 90
$\eta(1295)$	00^-	1294 ± 4*	$\eta_{\mathrm{N}}^E \to \eta\pi\pi + \eta'\pi\pi + \pi KK$	7 ± 3
$\eta(1440)$	00^-	1432 ± 10*	$\eta_{\mathrm{S}}^E \to K^\star K$	128^{+204}_{-128}
			$\eta_{\mathrm{S}}^E \to KK\pi$	28^{+41}_{-28}
			$\eta_{\mathrm{S}}^E \to \eta\pi\pi$ and $\eta'\pi\pi$	suppressed
			Total	156^{+245}_{-156}
σ_{S}^E (no assignment since no experimental candidate with congruent mass/width)	00^+	2038 ± 24	$\sigma_{\mathrm{S}}^E \to KK$	24^{+46}_{-24}
			$\sigma_{\mathrm{S}}^E \to \eta\eta'$	16 ± 3
			$\sigma_{\mathrm{S}}^E \to \eta\eta$	7 ± 1
			$\sigma_{\mathrm{S}}^E \to K_1 K$	4^{+8}_{-4}
			$\sigma_{\mathrm{S}}^E \to \eta'\eta'$	1 ± 0
			$\sigma_{\mathrm{S}}^E \to \pi\pi$, $\rho\rho$ and $\omega\omega$	suppressed
			$\sigma_{\mathrm{S}}^E \to a_1(1260)\pi$ and $f_1(1285)\eta$	suppressed
			$\sigma_{\mathrm{S}}^E \to \pi^E\pi$ and $\eta_{\mathrm{N}}^E\eta$	suppressed
			$\sigma_{\mathrm{S}}^E \to \sigma_{\mathrm{S}}\pi\pi$	suppressed
			Total	52^{+58}_{-32}
$K_0^{\star E}$ [tentatively assigned to the unconfirmed $K_0^\star(1950)$ resonance]	$\frac{1}{2}0^+$	2023 ± 27	$K_0^{\star E} \to \eta' K$	72 ± 12
			$K_0^{\star E} \to K\pi$	66 ± 46
			$K_0^{\star E} \to K_1\pi$	10 ± 7
			$K_0^{\star E} \to a_1(1260)K$	6 ± 4
			$K_0^{\star E} \to \eta K$	6^{+9}_{-6}
			$K_0^{\star E} \to f_1(1285)K$	2 ± 1
			$K_0^{\star E} \to K_1\eta$	0
			$K_0^{\star E} \to K_0^\star(1430)\pi\pi$	0
			Total	162^{+79}_{-76}

The results are summarised as follows (for more details, see Ref. [13]):

— The excited states are generally rather narrow. An exception is the result for the $f_0(1790)$ and $\eta(1440)$. Nonetheless, our decay width for $\Gamma_{f_0(1790)}$ is compatible with the LHCb data [10]. The large interval for the $\eta(1440)$ width is a consequence of parameter uncertainties induced by the large errors for $\Gamma_{f_0(1790)\to\pi\pi}$ and $\Gamma_{f_0(1790)\to KK}$, see above. These uncertainties also lead to extremely large errors [$\mathcal{O}(1\ \mathrm{GeV})$] of the decay widths of the excited pion and kaon. Hence these states are omitted from Table I.

We note, however, that if the excited pseudoscalars in the model are implemented to reproduce exactly the data on the putative experimental candidates [$\eta(1295)$, $\pi(1300)$, $\eta(1440)$, $K(1460)$], then all excited scalars become unmeasurably broad [widths $\mathcal{O}(1\ \mathrm{GeV})$]. Although this result is based on at times ambiguous experimental input and hence care is needed in its interpretation (see Ref. [13]), it appears to reveal tension between the simultaneous interpretation of $f_0(1790)/a_0(1950)$ and $\eta(1295)$, $\pi(1300)$, $\eta(1440)$ and $K(1460)$ as excited $\bar{q}q$ states.

— Our results predict $\Gamma_{a_0^E} = (280 \pm 90)$ MeV; this overlaps fully with $\Gamma_{a_0(1950)} = (271 \pm 40)$ MeV measured by the BaBar Collaboration [11]. Hence $a_0(1950)$, if confirmed, represents a very good candidate for an excited $\bar{q}q$ state.

— For $\eta(1295)$, the three decay widths accessible to our model (for $\eta_\mathrm{N}^E \to \eta\pi\pi + \eta'\pi\pi + \pi KK$) amount to (7 ± 3) MeV and hence contribute very little to the overall decay width $\Gamma_{\eta(1295)}^{\mathrm{total}} = (55 \pm 5)$ MeV.

— Our $\bar{s}s$ scalar isosinglet state σ_S^E has the same quantum numbers as the (unestablished [1]) resonances $f_0(2020)$ and $f_0(2100)$ but there is no mass/width overlap. Hence, they do not appear to represent unmixed excited quarkonia. The opposite is true for the (again unestablished) $K_0^\star(1950)$ resonance: since $m_{K_0^\star(1950)} = (1945 \pm 22)$ MeV and $\Gamma_{K_0^\star(1950)} = (201 \pm 90)$ MeV [1], it has a significant overlap with our excited scalar kaon $K_0^{\star E}$.

3. Conclusion

Results from the Extended Linear Sigma Model (eLSM) indicate that the $f_0(1790)$ and — if confirmed — also the $a_0(1950)$ and $K_0^\star(1950)$ resonances are largely unmixed excited $\bar{q}q$ states. The same is quite likely for $\eta(1295)$ and $\eta(1440)$ although overall, based on the current data, there appears to be tension between the simultaneous interpretation of $f_0(1790)/a_0(1950)$ and

$\eta(1295)$, $\pi(1300)$, $\eta(1440)$ and $K(1460)$ as excited $\bar{q}q$ states. Uncertainties in these conclusions come from (i) possible glueball admixture and (ii) scarcity of experimental data that can hopefully be amended by PANDA [15] and NICA [16].

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