The quest for light scalar quarkonia from an $N_f = 3$ linear sigma model with vectors and axial-vectors

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We address the question whether it is possible to interpret the low-lying scalar mesons $f_0(600)$ and $a_0(980)$ as $\bar{q}q$ states within a $U(3)\times U(3)$ Linear Sigma Model containing vector and axial-vector degrees of freedom.

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1. Introduction

Debate regarding the structure of scalar mesons has lasted for several decades but still without a clear-cut result. Experimental data [1] suggest the existence of at least seven $IJ^P = 00^+$ states in the region up to 1.75 GeV. These states are important both in vacuum phenomenology as well as in the restoration of the Chiral Symmetry of the QCD that is spontaneously broken in vacuum. Additionally, the larger-than-expected number of isoscalars in vacuum implies that not all of them can be $\bar{q}q$ states. In this work, we discuss a possibility to identify the elusive scalar quarkonia.

2. The Model and its Implications

We utilise a $U(3)_L \times U(3)_R$ linear sigma model with vectors and axial-vectors *both in the non-strange and strange sectors* [2, 3]:

$$\begin{aligned}
\mathscr{L} &= \mathrm{Tr}[(D^\mu\Phi)^\dagger(D^\mu\Phi)] - m_0^2\mathrm{Tr}(\Phi^\dagger\Phi) - \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)^2 \\
&- \tfrac{1}{4}\mathrm{Tr}[(L^{\mu\nu})^2 + (R^{\mu\nu})^2] + \mathrm{Tr}\left[\left(\tfrac{m_1^2}{2} + \Delta\right)(L^\mu)^2 + (R^\mu)^2\right] + \mathrm{Tr}[H(\Phi + \Phi^\dagger)] \\
&+ c_1(\det\Phi - \det\Phi^\dagger)^2 + i\tfrac{g_2}{2}(\mathrm{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \mathrm{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\}) \\
&+ \tfrac{h_1}{2}\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}[(L^\mu)^2 + (R^\mu)^2] + h_2\mathrm{Tr}[(\Phi R^\mu)^2 + (L^\mu\Phi)^2] + 2h_3\mathrm{Tr}(\Phi R_\mu \Phi^\dagger L^\mu)
\end{aligned} \tag{2.1}$$

where

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{(\sigma_N + a_0^0) + i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_S^+ + iK^+ \\ a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0) + i(\eta_N - \pi^0)}{\sqrt{2}} & K_S^0 + iK^0 \\ K_S^- + iK^- & \bar{K}_S^0 + i\bar{K}^0 & \sigma_S + i\eta_S \end{pmatrix} \tag{2.2}$$

is a matrix containing the scalar and pseudoscalar degrees of freedom, $L^\mu = V^\mu + A^\mu$ and $R^\mu = V^\mu - A^\mu$ are, respectively, the left-handed and the right-handed matrices containing vector and axial-vector degrees of freedom with

$$V^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_N + \rho^0}{\sqrt{2}} & \rho^+ & K^{\star+} \\ \rho^- & \frac{\omega_N - \rho^0}{\sqrt{2}} & K^{\star 0} \\ K^{\star-} & \bar{K}^{\star 0} & \omega_S \end{pmatrix}^\mu, A^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{f_{1N} + a_1^0}{\sqrt{2}} & a_1^+ & K_1^+ \\ a_1^- & \frac{f_{1N} - a_1^0}{\sqrt{2}} & K_1^0 \\ K_1^- & \bar{K}_1^0 & f_{1S} \end{pmatrix}^\mu \tag{2.3}$$

and $\Delta = \mathrm{diag}(\delta_N, \delta_N, \delta_S)$ describes explicit breaking of the chiral symmetry in the (axial-)vector channel. The explicit symmetry breaking in the (pseudo)scalar sector is described by $\mathrm{Tr}[H(\Phi + \Phi^\dagger)]$ with $H = 1/2\,\mathrm{diag}(h_{0N}, h_{0N}, \sqrt{2}h_{0S})$, $h_{0N} = const.$, $h_{0S} = const$. Also, $D^\mu\Phi = \partial^\mu\Phi - ig_1(L^\mu\Phi - \Phi R^\mu)$ is the covariant derivative; $L^{\mu\nu} = \partial^\mu L^\nu - \partial^\nu L^\mu$, $R^{\mu\nu} = \partial^\mu R^\nu - \partial^\nu R^\mu$ are, respectively, the left-handed and right-handed field strength tensors and the term $c_1(\det\Phi - \det\Phi^\dagger)^2$ describes the $U(1)_A$ anomaly [3]. All the states present in Eqs. (2.2) and (2.3) are $\bar{q}q$ states [2].

The assignment of the fields in the model is discussed in Ref. [3]. In this work it suffices to note that Eq. (2.2) contains two scalars: $\sigma_N = \bar{n}n$ and $\sigma_S = \bar{s}s$ (n and s denote nonstrange and strange quarks, respectively). Mixing of σ_1 and σ_2 produces states denoted henceforth as σ_1 (predominantly $\bar{n}n$) and σ_2 (predominantly $\bar{s}s$). As described in Ref. [3], σ_1 and σ_2 can be assigned either to the pair $\{f_0(600), f_0(1370)\}$ [conversely: $f_0(600)$ is predominantly a $\bar{n}n$ state and $f_0(1370)$ is predominantly a $\bar{s}s$ state] or to the pair $\{f_0(1370), f_0(1710)\}$ [conversely: $f_0(1370)$ is predominantly a $\bar{n}n$ state and $f_0(1710)$ is predominantly a $\bar{s}s$ state].

Assumption I: Scalars below 1 GeV are $\bar{q}q$ states. A fit is needed to determine model parameters in Eq. (2.1). It includes all states except for $\sigma_{1,2}$. It enforces that $\vec{a}_0 = a_0(980)$ and $K_S = K_0^\star(800)$ in Eq. (2.2). Then decay widths are calculated. We obtain satisfying results in the decay channels $\sigma_{1,2} \to \pi\pi$ and $\sigma_{1,2} \to KK$ if we set $m_{\sigma_1} = 705$ MeV and $m_{\sigma_2} = 1200$ MeV leading to $\Gamma_{\sigma_1 \to \pi\pi} = 305$ MeV and $\Gamma_{\sigma_2 \to \pi\pi} = 207$ MeV in the former and $\Gamma_{\sigma_1 \to KK} = 0$ and $\Gamma_{\sigma_2 \to KK} = 240$ MeV in the latter channel. These results correspond well to the data [1]. The results also suggest, however, that $f_0(1370)$ should predominantly decay into kaons (as $\Gamma_{\sigma_2 \to KK}/\Gamma_{\sigma_2 \to \pi\pi} = 1.15$) – not surprising for a predominantly $\bar{s}s$ state but clearly at odds with data [1].
An even larger problem arises in the (axial-)vector channel. The model exhibits interdependence of $\Gamma_{a_1(1260) \to \rho\pi}$ and $\Gamma_{\rho \to \pi\pi}$ [3]. We obtain $\Gamma_{a_1(1260) \to \rho\pi} > 10$ GeV if we set $\Gamma_{\rho \to \pi\pi} = 149.1$ MeV (as suggested by Ref. [1]). Alternatively, if one forces $\Gamma_{a_1(1260) \to \rho\pi} < 600$ MeV to comply with the data, then $\Gamma_{\rho \to \pi\pi} < 38$ MeV is obtained – approximately 100 MeV less than the PDG value.
Thus the assumption of scalar $\bar{q}q$ states below 1 GeV is strongly disfavoured.

Assumption II: Scalars above 1 GeV are $\bar{q}q$ states. We calculate our parameters as above; however, we now consider $\vec{a}_0 = a_0(1450)$ and $K_S = K_0^\star(1430)$ in Eq. (2.2). i.e., scalar $I = 1$ and $I = 1/2$ states are now assumed above 1 GeV.
The overall fit is better than in the previous case. We observe σ_1 as a broad resonance: $\Gamma_{\sigma_1 \to \pi\pi} \simeq (200-350)$ MeV for $m_{\sigma_1} \in [1200, 1500]$ MeV. We thus assign σ_1 to $f_0(1370)$. The state σ_2 corresponds to $f_0(1710)$: the PDG suggests $\Gamma^{\text{exp.}}_{f_0(1710) \to \pi\pi} = (29.28 \pm 6.53)$ MeV [1] yielding $m^{(1)}_{\sigma_2} = 1613$ MeV and $m^{(2)}_{\sigma_2} = 1677$ MeV; m_{σ_2} is very close to $m^{\text{exp.}}_{f_0(1710)} = (1720 \pm 6)$ MeV. We thus conclude that $f_0(1370)$ is predominantly a $\bar{n}n$ state and that $f_0(1710)$ is predominantly a $\bar{s}s$ state.
We also observe that $\Gamma_{a_1(1260) \to \rho\pi}$ is dramatically smaller than in the previous case: we obtain $\Gamma_{a_1(1260) \to \rho\pi} \simeq 860$ MeV. This is admittedly larger than 250 MeV $\leq \Gamma^{\text{exp.}}_{a_1(1260)} \leq 600$ MeV [1]. However, only a small change of $\Gamma_{\rho \to \pi\pi}$ is necessary in this case for $\Gamma_{a_1(1260) \to \rho\pi}$ to be within the data: $\Gamma_{a_1(1260) \to \rho\pi} = 590$ MeV is obtained for $\Gamma_{\rho \to \pi\pi} = 129$ MeV (previously: $\Gamma_{\rho \to \pi\pi} = 38$ MeV).

3. Summary and Outlook

We have presented a $U(3)_L \times U(3)_R$ Linear Sigma Model with (axial-)vector mesons. Structure of scalar states $f_0(600)$, $f_0(1370)$ and $f_0(1710)$ has been discussed within the model. Our results suggest that $f_0(1370)$ and $f_0(1710)$ are strongly favoured as predominantly $\bar{n}n$ and $\bar{s}s$ states, respectively, whereas the consideration of $f_0(600)$ and $f_0(1370)$ as predominantly $\bar{n}n$ and $\bar{s}s$ states, respectively, yielded unphysically broad $a_1(1260)$ state (decay width > 10 GeV).
Further calculations may include, e.g, a glueball field mixing with the already-present $\bar{q}q$ states.

References

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