MULTICHANNEL DESCRIPTION OF LIGHT AND INTERMEDIATE SCALAR MESONS

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Abstract

The light scalar mesons in a variety of approaches are briefly reviewed, as well as their description in the Resonance-Spectrum Expansion and related coupled-channel formalisms. A recent multichannel modelling of the light scalars is extended to higher energies and with additional decay channels, allowing to make predictions for the intermediate scalar mesons as well. Prospects for further improvements are discussed.

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1 Introduction to Scalar Mesons

The light scalar mesons represent nowadays one of the hottest topics in hadronic physics. Despite the growing consensus on the existence of a complete light scalar nonet, comprising the $f_0(600)$ (alias $\sigma$), $K^*_0(800)$ (alias $\kappa$), $a_0(980)$ and $f_0(980)$, which are now all included [1] in the PDG tables, their interpretation and possible dynamical origin in the context of QCD-inspired methods and models remains controversial. Moreover, their classification with respect to the intermediate scalars $f_0(1370)$, $K^*_0(1430)$, $a_0(1450)$ and $f_0(1500)$ [1] is also subject to continued debate. Thus, before presenting our actual model calculations, a brief historical discussion of the main theoretical and phenomenological approaches to the light scalars appears quite opportune, facing this audience that covers many different fields of expertise. Of course, time and space limitations do not allow an exhaustive treatment here.

What makes the light scalars so awkward for quark-model builders is not only their “lightness”, as their masses would rather be expected in the 1.3–1.5 GeV region, for conventional $^3P_0$ $q\bar{q}$ states, but also the fact that the isoscalar $\sigma$ meson is much lighter than the isovector $a_0(980)$. Moreover, the obviously nonstrange quark content of the $a_0(980)$ makes it very difficult to understand its approximate mass degeneracy with the $f_0(980)$, which is dominantly an $ss$ state, as can be inferred e.g. from the non-observation [1] of the decay $a_1(1260) \rightarrow f_0(980)\pi$, whereas the process $a_1(1260) \rightarrow \sigma\pi$ is seen [1].

These three problems were seemingly solved simultaneously in Jaffe’s [2] $qq\bar{q}\bar{q}$ proposal for ground-state scalar mesons, more than 30 years ago. Namely, a very strong and attractive
colour-hyperfine interaction for the lowest scalar \( q^2\bar{q}^2 \) (alias tetraquark) states could explain their low masses, while the mass degeneracy of the \( a_0(980) \) and \( f_0(980) \) would follow naturally from both having an \( u_i\bar{u}_j s\bar{s} \) configuration, where \( u_i,j \) stands for \( u \) or \( d \). Also the fact that the \( \sigma \) is lighter than the \( a_0(980) \) could then be easily explained from the smaller hyperfine attraction in the \( a_0(980) \), owing to the presence of the (heavier) strange quarks in the latter.

However, notwithstanding the originality and elegance of Jaffe’s idea, a serious problem, which also plagues the many recent yet similar tetraquark models, is its disregard of unitarisation effects. In other words, the coupling to physical decay channels, which e.g. produce the huge widths of the \( \sigma \) and the \( \kappa \), will almost inevitably give rise to real mass shifts of at least the same order, i.e., of (many) hundreds of MeVs. Therefore, as long as tetraquarks are not unitarised — and we are not aware of any attempt to do so — such models can only be considered qualitative, at best.

A completely different description of the light scalars is due to Scadron and Delbourgo [3], based on dynamical chiral-symmetry breaking. In their Bethe-Salpeter approach, the very same mechanism that makes the pion massless in the chiral limit, while giving the light quarks their dynamical mass, straightforwardly leads to a \( \sigma \) mass \( m_\sigma = 2m_{\text{dyn}} \) in the same limit, just like in the Nambu–Jona-Lasinio [4] model. More recently, Delbourgo and Scadron [5] formulated a similar picture in a non-perturbative and self-consistent field-theoretic way, via the quark-level linear \( \sigma \) model (QLL\( \sigma \)M), both for \( SU(2) \) and for \( SU(3) \), thus predicting a complete light scalar nonet having masses compatible with present-day experiment. Note that in this formalism at least some coupled-channel effects are already accounted for, through meson-loop contributions that recover tree-level results by construction, via a non-perturbative bootstrap [5].

Another totally alternative view is the generation of at least some of the light scalars as dynamical resonances of two pseudoscalar (P) mesons. In particular, the \( a_0(980) \) and \( f_0(980) \) are described as a kind of \( K\bar{K} \) molecules, owing to \( K\bar{K} \) potentials that are either effective or mainly based on \( t \)-channel vector-meson exchange. In the former approach, due to Weinstein and Isgur [6], the meson-meson interactions were extracted from a \( q^2\bar{q}^2 \) system and couplings to \( q\bar{q} \) scalar mesons. In the latter purely mesonic approach, due to Janssen, Pearce, Holinde and Speth [7], even a kind of \( \sigma \) was found, though too light and a bit too broad, with a pole at \((387-i305)\) MeV. However, no \( \kappa \) pole was reported.

A more empirical but also interesting approach is due to Anisovich (V. V.), Anisovich (A. V.), Sarantsev and co-workers [8], who carried out \( K \)-matrix analyses of \( S \)-wave PP scattering data, thereby identifying the \( K \)-matrix poles with the bare scalar \( q\bar{q} \) states that should follow from quark-antiquark (or gluon-gluon) interactions only. Although the idea to try to extract information on “quenched-QCD” spectra from scattering data is very appealing, and goes way beyond the traditional, naive approach to meson spectroscopy, the identification of \( K \)-matrix poles with bare states puzzles us. Namely, \( K \)-matrix poles correspond to the real energies at which the meson-meson phase shift passes through \( 90^\circ \), but bare states do not couple at all to the continuum and so for these there simply is no phase shift. We rather believe the bare states are at the real energies where (some) \( S \)-matrix poles end up if one manages to continuously turn off the coupling to the continuum. We shall come back to this point below. Anyhow, the distorted scalar nonets inferred from the analyses in Ref. [8], missing the \( \sigma \) and the \( \kappa \), already hint at problems with the \( K \)-matrix identification.

A phenomenological chiral model has been developed by Schechter and collaborators [9], in which a crossing-symmetric amplitude is constructed by summing a current-algebra contact term and leading resonance pole exchanges. Inclusion of “putative” light scalar mesons then satisfies unitarity bounds to well above 1 GeV, and allows good fits to the data.
Another formalism based on effective chiral Lagrangians is the work by Oller, Oset and Peláez [10], which is often called unitarised chiral perturbation theory (ChPT). Amplitudes from leading-order or next-to-leading-order ChPT are unitarised via multichannel Lippmann-Schwinger equations or other coupled-channel methods. After fitting the parameters to the available data, a nonet of light scalar mesons shows up as dynamical resonance poles, though the $f_0(980)$ needs a preexisting bare state in one of the formulations (N/D method).

Recently, a prediction for the $\sigma$ pole was obtained by Caprini, Colangelo and Leutwyler (CCL) [11], via Roy equations applied to the $I=0$ and $I=2$ $\pi\pi$ scattering amplitudes. The Roy equations amount to a twice-subtracted dispersion relation, so that some input from theory or experiment is needed to fix the subtraction constants, for which CCL took predictions from ChPT. The resulting $\sigma$ pole position of $(441^{+16}_{-8} - i272^{+9}_{-12.5})$ MeV is somewhat on the low [1] side as for its real part. Moreover, the claimed small errors seem too optimistic, mainly because of the incomplete treatment of the $K\bar{K}$ channel, which opens far below the energy at which the integrals are cut off (1.4 GeV), but also in view of the uncertainties concerning the true scattering lengths, the cut-off high-energy (> 1.4 GeV) tail of the dispersion integral, and the contributions of higher partial waves.

Already many years earlier, two independent unitarised quark models were developed and applied to the scalar sector, namely by the Helsinki group, led by Törnqvist [12], and several people from Nijmegen [13], including two of the present authors. In the Törnqvist approach, for each isospin a bare scalar $q\bar{q}$ state in the 1.4–1.6 GeV region is coupled to all available PP channels, using $SU(3)$-symmetric coupling constants. As a result, some dynamical resonances show up at much lower energies, alongside the unitarised states at the normal energies for $^3P_0$ $q\bar{q}$ states. Originally, this only allowed to generate the $a_0(980)$ and $f_0(980)$ (Ref. [12], 1st paper). Much later, inclusion of the Adler-Weinberg zero in the isoscalar case then also resulted in a light and broad $\sigma$, with pole position $E = (470 - i250)$ MeV (Ref. [12], 2nd and 3rd paper). However, no $\kappa$ was found in the latter analysis either, which was probably due to the inclusion of an unphysical Adler zero at a negative value of $s = E^2$ [14].

In the original Nijmegen approach [13], one or more confined $q\bar{q}$ channels were coupled to all available PP as well as vector-vector (VV) channels, with confinement modelled through a harmonic-oscillator (HO) potential having flavour-independent spacings. Unitarisation then leads to a distortion of the bare HO spectrum, and in the scalar case even gives rise to a doubling of all ground states, resulting in a complete light scalar nonet, including the $\kappa$, with pole positions $(470 - i208)$ MeV ($\sigma$), $(727 - i263)$ MeV ($\kappa$), $(994 - i20)$ MeV ($f_0(980)$) and $(968 - i28)$ MeV ($a_0(980)$). These parameter-free predictions from more than 20 years ago are still close to the present-day world averages. Also note that the same model predicted earlier [15] a long controversial $\rho(1250)$ resonance, which was very recently confirmed [16] in a multichannel analysis of $P$-wave $\pi\pi$ data.

2 Resonance-Spectrum-Expansion Model

A modern formulation of the coupled-channel model employed in Ref. [15] is the Resonance-Spectrum Expansion (RSE) [17], in which mesons in non-exotic channels scatter via an infinite set of intermediate $s$-channel $q\bar{q}$ states, i.e., a kind of Regge propagators [18]. The confinement spectrum for these bare $q\bar{q}$ states can, in principle, be chosen freely, but in all phenomenological applications so far we have used an equidistant HO spectrum, as in Refs. [15] and [13]. Because of the separability of the effective meson-meson interaction, the RSE model can be solved in closed form. The relevant Born and one-loop diagrams are depicted in Fig. 1, from which it is obvious that one can straightforwardly sum up the complete Born series. For the meson-meson–quark-antiquark vertex functions we take a delta shell in coordinate space,
which amounts to a spherical Bessel function in momentum space. Such a transition potential represents the breaking of the string between a quark and an antiquark at a certain distance $r_0$, with overall coupling strength $\lambda$, in the context of the $^3P_0$ model.

Spectroscopic applications of the RSE are manifold. In the one-channel formalism, the $\kappa$ was once again predicted in 2001 (Ref. [19], 1st paper), a year before its experimental confirmation. In the 2nd paper of Ref. [19], the low mass of the $D_{s0}^*(2317)$ was shown to be due to its strong coupling to the $S$-wave $DK$ threshold, an explanation that is now widely accepted. The 3rd paper of Ref. [19] presented a similar solution to the whole pattern of masses and widths of the charmed axial-vector mesons.

Multichannel versions of the RSE model have been employed to produce a detailed fit of $S$-wave PP scattering and a complete light scalar nonet (Ref. [20], 1st paper), with very few parameters (also see below), and to predict the $D_{sJ}(2860)$ (Ref. [20], 2nd paper), shortly before its observation was publicly announced.

Finally, the RSE has recently been applied to production processes [21] as well, in the spectator approximation. Most notably, it was shown that the RSE results in a complex relation between production and scattering amplitudes (papers 1–3 in Ref. [21]). Successful applications include the extraction of $\kappa$ and $\sigma$ signals from data on 3-body decay processes (4th paper in Ref. [21]), the deduction of the string-breaking radius $r_0$ from production processes at very different energy scales (5th paper), and even the discovery of signals hinting at new vector charmonium states in $e^+e^- \rightarrow \Lambda_c\bar{\Lambda}_c$ data (6th paper).

3 Light and Intermediate Scalar Mesons

3.1 Published results for $S$-wave PP scattering

In Ref. [20], 1st paper, hereafter referred to as BBKR, two of us (EvB, GR) together with Bugg and Kleefeld applied the RSE to $S$-wave PP scattering up to 1.2 GeV, coupling the channels $\pi\pi$, $KK$, $\eta\eta$, $\eta'\eta'$ for $I=0$, $K\pi$, $K\eta$, $K\eta'$ for $I=1/2$, and $\eta\pi$, $KK$, $\eta\pi$ for $I=1$. Moreover, in the isoscalar case both an $n\bar{n}$ and an $s\bar{s}$ channel were included, so as to allow dynamical mixing to occur via the $KK$ channel. The very few parameters, essentially only the overall coupling $\lambda$ and the transition radius $r_0$, were fitted to scattering data from various sources, for $I=0$ and for $I=1/2$, and to the $a_0(980)$ line shape, determined in a previous analysis, for $I=1$. Moreover, the parameters $\lambda$ and $r_0$ varied less than $\pm 10\%$ from one case to another. Overall, a good description of the data was achieved (see BBKR for details).

Poles for the light scalars were found at (all in MeV)

$$\sigma: 530 - i226, \quad \kappa: 745 - i316, \quad f_0(980): 1007 - i38, \quad a_0(980): 1021 - i47.$$ 

No pole positions for the intermediate scalar mesons were reported in BBKR, as the fits were only carried out to 1.1 GeV in the isovector case, and to 1.2 GeV in the others. Nevertheless, corresponding poles at higher energies were found, but these were of course quite unreliable.

In the following, we shall present very preliminary results for fits extended to higher energies, and with more channels included.
3.2 Isoscalar scalar resonances with PP and VV channels included

For $I = 0$, the VV channels that couple to $n\bar{n}$ and/or $s\bar{s}$ are $\rho\rho$, $\omega\omega$, $K^*\bar{K}^*$ and $\phi\phi$, for both $L = 0$ and $L = 2$. The corresponding expression for the $T$-matrix is quite complicated (see Eqs. (4) and (5) in BBKR). We fit the parameters $\lambda$ and $r_0$ to sets of $S$-wave $\pi\pi$ phase shifts compiled by Bugg and Surovtsev [22], which yield a somewhat larger scattering length than in BBKR, viz. $0.21m_\pi^{-1}$. The result of the fit is shown in Fig. 2, together with the curve from BBKR, where only PP channels were included and somewhat lower data were used just above the $\pi\pi$ threshold. The PP+VV fit is excellent up to 1 GeV, but clearly lacks structure thereabove. Nevertheless, inclusion of the VV channels does take care of the unrealistic “bump” around the $\eta\eta'$ threshold in the case of the PP fit (up to 1.2 GeV) of BBKR (dashed curve in Fig. 2). The deficient behaviour of the PP+VV phase above 1 GeV seems to be mostly due to a too low-lying pole for the $f_0(1370)$ and a too broad one for the $f_0(1500)$. The first four isoscalar poles we find are (all in MeV)

$$
\sigma : 456 - i234 , \quad f_0(980) : 994 - i57 , \quad f_0(1370) : 1212 - i104 , \quad f_0(1500) : 1517 - i194 .
$$

3.3 $a_0(980)$ and $a_0(1450)$

In the isotriplet case, we fit $\lambda$ and $r_0$, as well as the pseudoscalar mixing angle, to the $a_0(980)$ line shape, just as in BBKR, but now with the VV channels ($\rho K^*$, $\omega K^*$, $\phi K^*$) added. Thus, the quality of the fit is further improved, and also the fitted mixing angle $\theta_{PS} = 43.7^\circ$ (flavour basis) becomes more realistic. The poles we find are (1018 $- i44$) MeV (second sheet) for the $a_0(980)$ and $1410 - i261$ MeV for the $a_0(1450)$, the latter being quite a bit too broad.

3.4 $K_0^*(800)$ and $K_0^*(1430)$

Including the vector channels ($\rho K^*$, $\omega K^*$, $\phi K^*$) in the isodoublet sector does not improve the fit, on the contrary. This will require a detailed investigation, which lies beyond the scope of this presentation. Thus, we limit ourselves to extend the PP fit from BBKR up to 1.5 GeV, using the full LASS data, instead of the ones with the effect of the $K_0^*(1430)$ subtracted. Then, a good fit is obtained, with the very realistic pole positions (758 $- i295$) MeV for the $\kappa$ and (1410 $- i124$) MeV for the $K_0^*(1430)$.

4 Conclusions and outlook

The preliminary results in this study indicate that a good description of both the light and the intermediate scalar mesons is feasible in the RSE, taking into account additional sets of coupled channels that should become relevant at higher energies. However, for a detailed description of phase shifts above 1 GeV, it may be necessary to include scalar-scalar channels as well, e.g. to effectively deal with (part of the) $4\pi$ decays in the isoscalar case. This could
also require a procedure to make certain thresholds less sharp, in order to account for the large widths of some final-state resonances.

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Note, however, that the $K^*_0(800)$ is still inexplicably omitted from the Summary Table, while its quoted “average” mass of $(672 \pm 40)$ MeV makes no sense whatsoever, in view of the recent experimental convergence towards a value of roughly 800 MeV.

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