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SCALAR MESONS: FIFTY YEARS OF CHALLENGING THE QUARK MODEL*

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Half a century of work on the light scalar mesons $f_0(500)$, $f_0(980)$, $K_0^\star(700)$, and $a_0(980)$ is briefly reviewed. After summarising all light scalar candidates in the Review of Particle Physics since 1963, a selection of different theoretical and phenomenological descriptions is presented, including pure meson–meson models, a tetraquark construction, unitarised quark–meson models, unitarised effective chiral approaches, and a very recent lattice-QCD simulation.

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The light scalar-meson nonet $f_0(500)$ (alias σ), $f_0(980)$, $K_0^\star(700)$ (alias κ), and $a_0(980)$ [1] has been vexing experimentalists as well as theorists for more than fifty years by now. Especially the isoscalar σ and isodoublet κ in S-wave $\pi\pi$ and $K\pi$ scattering, respectively, have for many years been considered doubtful as genuine resonances. Only very recently [1], the κ meson was included in the PDG Meson Summary Table of the Review of Particle Physics (RPP). But also the isoscalar $f_0(980)$ and isovector $a_0(980)$ have for several years been questioned. In Table I, we list all light scalars that have appeared in the PDG tables since the earliest RPP days, including states with uncertain J^{PC} or even initially identified as having $J \geq 1$. The reported masses and widths or pole positions, when available, can be found in the corresponding references. Only those PDG editions are included in the table that report any change of one or more scalar entries with respect to the previous edition.

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TABLE I

The light scalar-meson nonet in *The Review of Particle Physics* /(RPP). $^\dagger J^{PC} = 0^{++}?$, $^\ddagger J^{PC}$ unknown, $^{\dagger\dagger} J^{PC} = (\mathrm{Even})^{++}$, $^{\ddagger\ddagger} J \geq 1$; $J^{PC} = 0^{++}$ otherwise.

Year	$f_0(500)$	$K_0^\star(700)$	$f_0(980)$	$a_0(980)$
1963 [2]	$\omega_{ABC}(317)^\ddagger$	$K_1^{**}(730)^{\ddagger\ddagger}$	$\kappa_2(1040)^{\dagger\dagger}$	$\chi_1(1045)^\ddagger$
1963 [3]	$\omega_{ABC}(317)$	$\kappa(725)^{\ddagger\ddagger}$	$?(1040)^{\dagger\dagger}$	$?^-(1000)^\ddagger$
1964 [4]	$\sigma(390)^\dagger$	$\kappa(725)^\ddagger$	$K_1K_1(1020)^{\dagger\dagger}$	—
1965 [5]	{ $\sigma(390)^\dagger$ $S0(\pi\pi,700)$	$\kappa(725)^\ddagger$	$K_1K_1(1020)^{\dagger\dagger}$	—
1966 [6]	{ $\sigma(390)^\dagger$ $S^0(720)$	$\kappa(725)^\ddagger$	$K\bar{K}_0(1068)$	—
1967 [7]	{ $\sigma(410)$ $\epsilon(700)$	$\kappa(725)^\ddagger$	$\eta_V(1050)$	$\delta(965)^\ddagger$
1968 [8]	{ $\sigma(410)$ $\epsilon(730)$	$\kappa(725)^\ddagger$	$\eta_V(1070)$	{ $\delta(963)^\ddagger$ $\pi_N(1016)$
1969 [9]	{ $\sigma(410)$ $\eta_{0+}(720)$	$\kappa(725)^\ddagger$	$\eta_{0+}(1070)$	{ $\delta(963)^\ddagger$ $\pi_N(1016)$
1970 [10]	{ $\sigma(410)$ $\eta_{0+}(700)$	$\kappa(725)^\ddagger$	$\eta_{0+}(1060)$	{ $\delta(962)^\ddagger$ $\pi_N(1016)$
1970 [11]	{ $\sigma(410)$ $\eta_{0+}/\epsilon(700)$	$\kappa(725)^\ddagger$	$\eta_{0+}/S^\star(1060)$	{ $\delta(966)^\ddagger$ $\pi_N(1016)$
1971 [12]	{ $\sigma(410)$ $\eta_{0+}/\epsilon(700\text{–}1000)$	$\kappa(725)^\ddagger$	$\eta_{0+}/S^\star(1070)$	{ $\delta(962)^\ddagger$ $\pi_N(1016)$
1972 [13]	ϵ	κ	$S^\star(1000)$	$\pi_N(975)$
1973 [14]	ϵ	κ	$S^\star(997)$	$\delta(970)$
1974 [15]	ϵ	κ	$S^\star(993)$	$\delta(970)$
1976 [16]	$\epsilon(1200)$	$\kappa(1250)$	$S^\star(993)$	$\delta(970)$
1978 [17]	$\epsilon(1300)$	$\kappa(1400)$	$S^\star(980)$	$\delta(980)$
1980 [18]	$\epsilon(1300)$	$\kappa(1500)$	$S^\star(980)$	$\delta(980)$
1982 [19]	$\epsilon(1300)$	$\kappa(1350)$	$S^\star(975)$	$\delta(980)$
1984 [20]	$\epsilon(1300)$	$\kappa(1350)$	$S/S^\star(975)$	$\delta(980)$
1986 [21]	$f_0(1300)$	$K_0^\star(1350)$	$f_0(975)$	$a_0(980)$
1988 [22]	$f_0(1400)$	$K_0^\star(1430)$	$f_0(975)$	$a_0(980)$
1990 [23]	$f_0(1400)$	$K_0^\star(1350)$	$f_0(975)$	$a_0(980)$
1992 [24]	$f_0(1400)$	$K_0^\star(1430)$	$f_0(975)$	$a_0(980)$
1994 [25]	$f_0(1300)$	$K_0^\star(1430)$	$f_0(980)$	$a_0(980)$
1996 [26]	$f_0(400\text{–}1200)$	$K_0^\star(1430)$	$f_0(980)$	$a_0(980)$
2002 [27]	$f_0(600)$	$K_0^\star(1430)$	$f_0(980)$	$a_0(980)$
2004 [28]	$f_0(600)$	$K_0^\star(800)$	$f_0(980)$	$a_0(980)$
2012 [29]	$f_0(500)$	$K_0^\star(800)$	$f_0(980)$	$a_0(980)$
2018 [1]	$f_0(500)$	$K_0^\star(700)$	$f_0(980)$	$a_0(980)$

The difficulty in extracting the light scalar mesons from the data originates in Adler zeros in the associated S-wave amplitudes, overlapping resonances, and strong inelasticities. In the remainder of this brief review, we shall present a selection of theoretical and phenomenological modellings of the light scalars, as well as a very recent lattice calculation of the σ meson. For a much more comprehensive list of σ and κ works, see Ref. [30].

(1) *"Yang–Mills Fields and Pseudoscalar Meson Scattering", D. Iagolnitzer, J. Zinn-Justin, J.B. Zuber [31].*
A Lagrangian model for the scattering of pseudoscalar mesons is formulated, with exchanges of the vector mesons ρ, $K^\star$, and ϕ. The model is not renormalisable, so subtraction constants are used. Unitarisation is done applying the Padé method to Born plus one-loop diagrams. Fits to the data then yield, for S-wave scattering, the following scalar masses, widths (in MeV): $\epsilon(460, 675)$; $S^\star(990, 40)$; $\kappa(665, 840)$; $\pi_N(775, 610)$ (also see Table I).

(2) *"Multiquark Hadrons I. Phenomenology of $Q^2\bar{Q}^2$ Mesons", R.L. Jaffe [32].*
The light scalars are modelled as $q^2\bar{q}^2$ states in the MIT Bag Model. A very large attractive colour-hyperfine interaction results in the following low yet purely real masses (in MeV): $\epsilon(700)$; $S^\star(1100)$; $\kappa(900)$; $\delta(1100)$.

(3) *"Dynamical Symmetry Breaking and the Sigma-Meson Mass in Quantum Chromodynamics", R. Delbourgo, M.D. Scadron [33].*
The spontaneous breakdown of chiral symmetry is analysed dynamically via bound-state Bethe–Salpeter equations. While in general spontaneous mass generation is linked to a massless pseudoscalar pion and to no specific constraint on a massive scalar meson, for the particular theory of asymptotically free QCD, it is shown that a scalar σ meson should exist with mass $m_\sigma \approx 600$–700 MeV.

(4) *"A Low Lying Scalar Meson Nonet in a Unitarized Meson Model", E. van Beveren et al. [34].*
A unitarised quark model previously fitted to light and heavy pseudoscalar and vector mesons is applied to scalar mesons as normal P-wave $q\bar{q}$ states, with unaltered parameters. Apart from the standard scalars between 1.3 and 1.5 GeV, an additional nonet below 1 GeV is dynamically generated, with the following resonance pole positions (in MeV): $\epsilon(470 - i208)$, $S^\star(994 - i20)$, $\kappa(727 - i263)$, $\delta(968 - i28)$. These values are still compatible with present-day PDG limits.

(5) *"Relativistic Effects in Scalar Meson Dynamics", R. Kamiński, L. Leśniak, J.P. Maillet [35].*
A purely mesonic model for the coupled S-wave channels $\pi\pi$ and $K\bar{K}$, with phenomenological separable potentials, is solved through a relativistic Lippmann–Schwinger equation. Fitting the parameters to data yields the following masses, widths (in MeV):
$f_0(500)(506, 494)$; $f_0(980)(973, 29)$.

(6) *"Structure of the Scalar Mesons $f_0(980)$ and $a_0(980)$", G. Janssen, B.C. Pearce, K. Holinde, J. Speth [36].*
A Blankenbecler–Sugar equation is solved for S-wave $\pi\pi, K\bar{K}$, and $\pi\eta$ scattering, with t-channel vector-meson exchanges and s-channel scalar exchanges. Fits to the data result in the following poles (in MeV):
$\sigma(387 - i305)$; $f_0(980)(1015 - i15)$; $a_0(980)(991 - i101)$.

(7) *"Confirmation of the Sigma Meson", N.A. Tornqvist, M. Roos [37].*
Bare scalar $q\bar{q}$ states are coupled to channels of two pseudoscalar mesons, in a unitarised quark-meson model. Fitting the data predicts the following scalar-meson poles (in MeV): $\sigma(470 - i250)$; $f_0(980)$ $(1006 - i17)$; $a_0(980)(1094 - i145)$. Note: no κ pole found.

(8) *"Simple Description of $\pi\pi$ Scattering to 1 GeV", M. Harada, F. Sannino, J. Schechter [38].*
$\pi\pi$ amplitudes from an effective nonlocal chiral Lagrangian are written as a sum of a relativistic Breit–Wigner form plus a nonresonant background, with local unitarity and crossing symmetry satisfied. Fits produce the following scalar masses, widths (in MeV):
$\sigma(559, 370)$; $f_0(980)(980, 40–400)$.

(9) *"An Analysis of $\pi\pi$-Scattering Phase Shift and Existence of $\sigma(555)$ Particle", S. Ishida et al. [39].*
The unitary interfering-amplitude method is employed to describe S-wave $\pi\pi$ scattering, including a negative background phase instead of the usual Adler zero. For $f_0(980)$, the $\pi\pi \to K\bar{K}$ data are included, too. Fits give the following masses, widths (in MeV):
$\sigma(553, 243)$; $f_0(980)(993, \sim 100)$.

(10) *"Meson–Meson Interactions in a Nonperturbative Chiral Approach", J.A. Oller, E. Oset, J.R. Peláez [40].*
Amplitudes from $\mathcal{O}(p^2)$ and $\mathcal{O}(p^4)$ chiral Lagrangians are unitarised with the inverse-amplitude method. Fits to the S-wave data yield the following scalar-meson poles (in MeV):
$\sigma(442 - i272)$; $f_0(980)(994 - i14)$; $\kappa(770 - i250)$; $a_0(980)(1055 - i21)$.

(11) *"Comments on the σ and κ", D.V. Bugg [41].*

Relativistic Breit–Wigner forms with Adler zeros included in the energy-dependent widths are used to fit combined S-wave data from elastic scattering and production processes for $\pi\pi$, and elastic data only for $K\pi$. Resulting poles of σ and κ (in MeV):
$(533 \pm 25) - i(249 \pm 25)$, $(722 \pm 60) - i(386 \pm 50)$.

(12) *"Mass and Width of the Lowest Resonance in QCD", I. Caprini, G. Colangelo, H. Leutwyler [42].*
A twice-subtracted dispersion relation (Roy equation) is employed to extract a σ pole position from $\pi\pi$ data, while fixing the subtraction constants via chiral perturbation theory. Result:
$(441^{+16}_{-8} - i272^{+9}_{-12.5})$ MeV.

(13) *"Isoscalar $\pi\pi$ Scattering and the σ Meson Resonance from QCD", R.A. Briceno, J.J. Dudek, R.G. Edwards, D.J. Wilson [43].*
A lattice calculation of energy-dependent S-wave isoscalar $\pi\pi$ phase shifts is carried out satisfying elastic unitarity, with both $q\bar{q}$ and $\pi\pi$ interpolators included, for π masses of 391 and 236 MeV. A $\pi\pi$ bound state shows up in the former case and a broad resonance in the latter. This resonance resembles the σ meson, though its precise pole position depends on the employed parametrisation. Future work will aim at using even lighter u, d quarks and pions, besides imposing constraints from causality and crossing symmetry.

To conclude, in this minireview, we have summarised all RPP entries of light scalar-meson candidates, starting from the earliest available data. Moreover, a selection of typical and innovative model approaches has been provided, which we hope sheds some more light on the nature of these enigmatic mesons. Finally, a very recent lattice calculation appears to support their interpretation as strongly unitarised $q\bar{q}$ states, as pioneered in Ref. [34].

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