SCALAR MESONS

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Introduction: In contrast to the vector and tensor mesons, the identification of the scalar mesons is a long-standing puzzle. The number of publications since our last issue indicates great activity in that field. Scalar resonances are difficult to resolve because of their large decay widths causing a strong overlap between resonances and background, and at the same time, several decay channels open up within a short mass interval. In addition, especially the $\overline{K}K$ and $\eta\eta$ thresholds produce important sharp cusps in the energy dependence of the resonant amplitude. Furthermore, one expects non-$\overline{q}q$ scalar objects, like glueballs and multiquark states, in the mass range below 1800 MeV.

Scalars are produced, for example, in $\overline{p}p$ annihilation (high statistics), πN scattering on polarized/unpolarized targets, central production, J/ψ decays, D- and K-meson decays, $\gamma\gamma$ formation, and ϕ radiative decays. Experiments are accompanied by the development of theoretical models for the reaction amplitudes, which are based on common fundamental principles of two-body unitarity, analyticity, Lorentz invariance, and chiral- and flavor-symmetry using different techniques (K-matrix formalism, N/D-method, Dalitz Tuan ansatz, unitarized quark models with coupled channels, effective chiral field theories like the linear sigma model, etc.).

The mass and width of a resonance are found from the position of the nearest pole in the T matrix (or equivalently, in the S matrix) at an unphysical sheet of the complex energy plane: $(E - i\frac{\Gamma}{2})$. It is important to realize that only in the case of well-separated resonances, far away from the opening of decay channels, does the naive Breit-Wigner parameterization (or K-matrix pole parameterization) agree with the T-matrix pole position in the amplitude.

In this note, we discuss all light scalars organized in the listings under the entries ($I = 1/2$) $K^*(1430)$, ($I = 1$) $a_0(980)$, $a_0(1450)$, and ($I = 0$) σ or $f_0(400–1200)$, $f_0(980)$, $f_0(1370)$, and $f_0(1500)$. This list is minimal and does not necessarily exhaust the list of actual resonances. The ($I = 2$) $\pi\pi$ and ($I = 3/2$) $K\pi$ phase shifts do not exhibit any resonant behavior.

See also our notes in previous issues for further comments on *e.g.*, scattering lengths and older papers.

The $I = 1/2$ States: The $K^*(1430)$ (ASTON 88) is perhaps the least controversial of the light scalar mesons. The $K\pi$ phase shift rises smoothly from the threshold, passes 90° at 1350 MeV, and continues to rise to about 170° at 1600 MeV, the first important inelastic threshold $K\eta'(958)$. Thus, it behaves like a single broad, nearly elastic resonance. ABELE 98, analyzing the $\overline{K}K\pi$ channel of $\overline{p}p$ annihilation at rest, finds the T-matrix pole parameters, $m \approx 1430$ MeV and $\Gamma \approx 290$ MeV, while the K-matrix pole of the same data is about 1340 MeV. This agrees with the LASS (ASTON 88) determination.

It should, however, be noted that several authors (BLACK 98, 99, DELBOURGO 98, ISHIDA 99, OLLER 99,99C, BEVEREN 99) have introduced a light "$\kappa(900)$" meson, which in the model interferes destructively with a large background. This makes the existence of a such light state very model dependent.

The $I = 1$ States: Two isovector states are known, the established $a_0(980)$ and the $a_0(1450)$ found by the Crystal Barrel experiment (AMSLER 94D). Independently of any model about the nature of the $a_0(980)$, the $\overline{K}K$ component in the wave function of this state must be large: the $a_0(980)$ lies close to the opening of the $\overline{K}K$ channel to which it couples strongly. This gives an important cusp-like behavior in the resonant amplitude. Hence, its mass and width parameters are strongly distorted. To reveal its true coupling constants, a coupled channel model with energy-dependent widths and mass shift contributions must be applied.

In our previous editions, the relative coupling $\overline{K}K/\pi\eta$ was only determined indirectly from $f_1(1285)$ (CORDEN 78, DEFOIX 72) or $\eta(1410)$ decays (BAI 90C, BOLTON 92B, AMSLER 95C), or from the line shape observed in the $\pi\eta$ decay mode (FLATTE 76, AMSLER 94D, BUGG 94, JANSSEN 95). From the analysis of $\pi\pi\eta$ and $\overline{K}K\pi$ final states of $\overline{p}p$ annihilation at rest, a relative production ratio $B(\overline{p}p \to \pi a_0; a_0 \to \overline{K}K)/B(\overline{p}p \to \pi a_0; a_0 \to \pi\eta) = 0.23 \pm 0.05$ is obtained by (ABELE 98). Tuning of the couplings in a coupled channel formula to reproduce the production ratio for the integrated mass distributions gives a relative branching ratio $\Gamma(\overline{K}K)/\Gamma(\pi\eta) = 1.03 \pm 0.14$. The analysis of the $\overline{p}p$ annihilation data also found that the width determined from the T-matrix pole is 92 ± 8 MeV, while the observed width of the peak in the $\pi\eta$ mass spectrum is about 45 MeV. In all measurements listed in our table, the mass position agrees on a value near 980 MeV, but the width takes values between 50 and 300 MeV due to the different applied models.

The $a_0(1450)$ is seen by the Crystal Barrel experiment in its $\pi\eta$, $\overline{K}K$, and $\pi\eta'(958)$ decay modes. The relative couplings to the different final states are found to be close to SU(3)-flavor predictions for an ordinary $\overline{q}q$ meson. The OBELIX experiment (BERTIN 98B) finds two solutions in the $K_S K^\pm \pi^\mp$ final state of the $\overline{p}p$ annihilation, one at 1480 MeV and one with a mass value close to that of $a_2(1320)$, which is preferred by their fit, and by the low angular momentum in the production. The broad structure at about 1300 MeV observed in $\pi N \to \overline{K}KN$ reactions needs further confirmation in existence and isospin assignment.

The $I = 0$ States: The $I = 0$ $J^{PC} = 0^{++}$ sector is the most complex one, both experimentally and theoretically. The data have been obtained from $\pi\pi$, $\overline{K}K$, $\eta\eta$, 4π, and $\eta\eta'(958)$ systems produced in S wave. From the high-statistics data sets collected from $\overline{p}p$ annihilation at rest into $\pi^0 f_0$, where the f_0 decays into the channels mentioned above, one concludes that at least four poles are needed in the mass range from the $\pi\pi$ threshold to about 1600 MeV. The claimed isoscalar resonances are found under separate entries σ or $f_0(400–1200)$, $f_0(980)$, $f_0(1370)$, and $f_0(1500)$.

Below 1100 MeV, the important data come from the $\pi\pi$ and $\overline{K}K$ final states. Information on the $\pi\pi$ S-wave phase shift $\delta^I_J = \delta^0_0$ was already extracted 20 years ago from the

πN scattering with unpolarized (GRAYER 74) and polarized targets (BECKER 79), and near threshold from the K_{e4}-decay (ROSSELET 77). The $\pi\pi$ S-wave inelasticity is not accurately known, and the reported $\pi\pi \rightarrow \overline{K}K$ cross sections (WETZEL 76, POLYCHRONAKOS 79, COHEN 80, and ETKIN 82B) may have large uncertainties. The πN data (GRAYER 74, BECKER 79) have been reanalyzed in combination with the $\overline{p}p$ annihilation data (KAMINSKI 97). Two out of four relevant solutions are found, with the S-wave phase shift rising slower than the P wave [$\rho(770)$], which is used as a reference. One of these corresponds to the well-known "down" solution of GRAYER 74. The other "up" solution shows a decrease of the modulus in the mass interval between 800–980 MeV. Both solutions exhibit a sudden drop in the modulus and inelasticity at 1 GeV, due to the appearance of $f_0(980)$, which is very close to the opening of the $\overline{K}K$ threshold. The phase shift δ_0^0 rises smoothly up to this point, where it jumps by 120° (in the "up") or 140° (in the "down") solution to reach 230°, and then both continue to rise slowly.

SVEC 97 suggests the existence of a narrow state at 750 MeV, with a small width of 100 to 200 MeV in his analysis of the πN(polarized) data, from 600 to 900 MeV. Such a solution is also found by (KAMINSKI 97) using the CERN-Munich (-Cracow) data considering both the π- and $a_1(1260)$-exchange in the reaction amplitudes. However, they show that unitarity is violated for this solution. Therefore, a narrow, light f_0 state below 900 MeV is excluded (KAMINSKI 97, 00). Also, the $2\pi^0$ invariant mass spectra of the $\overline{p}p$ annihilation at rest (AMSLER 95, ABELE 96), and the central collision (ALDE 97), do not show a narrow resonance below 900 MeV, and these data are consistently described with the standard "down" solution (GRAYER 74, KAMINSKI 97), which allows for the existence of the broad ($\Gamma \approx 500$ MeV) σ listed under $f_0(400–1200)$. The σ is difficult to establish experimentally without models. It is expected to be very broad, and so can be easily distorted by large background from contact terms, crossed channel exchanges, the $f_0((1370)$, and other dynamical features. Further information on this object is expected from the analysis of three body decays of the D meson, *e.g.*, $D \rightarrow \sigma\pi \rightarrow 3\pi$ (E791 experiment).

The $f_0(980)$ interferes destructively with the background leading to a dip in the $\pi\pi$ spectrum at the $\overline{K}K$ threshold. It changes from a dip into a peak structure in the $\pi^0\pi^0$ invariant mass spectrum of the reaction $\pi^- p \rightarrow \pi^0\pi^0 n$ (ACHASOV 98E), with increasing four-momentum transfer to the $\pi^0\pi^0$ system, which means increasing the a_1-exchange contribution in the amplitude, while the π-exchange decreases.

A meson resonance very well studied experimentally, is the $f_0(1500)$, seen by the Crystal Barrel experiment in five decay modes: $\pi\pi$, $\overline{K}K$, $\eta\eta$, $\eta\eta'(958)$, and 4π (AMSLER 95D, ABELE 96, and ABELE 98). Due to its interference with the $f_0(1370)$, the peak attributed to $f_0(1500)$ can appear shifted in mass to 1590 MeV, where it was observed by the GAMS Collaboration (BINON 83) in the $\eta\eta$ mass spectrum. For the dynamics in the resonant amplitude, they applied a sum of Breit-Wigner functions. In the central production (ANTINORI 95), a peak at a mass of 1450 MeV, having a width of 60 MeV, can be interpreted as the coherent sum of $f_0(1370)$ and $f_0(1500)$. The $\overline{p}p$ and $\overline{n}p/\overline{p}n$ reactions show a single enhancement at 1400 MeV in the invariant 4π mass (GASPERO 93, ADAMO 93, AMSLER 94, and ABELE 96). In the $5\pi^0$ channel (ABELE 96), this structure was resolved into $f_0(1500)$ and $f_0(1370)$, where the latter was found at somewhat lower mass at around 1300 MeV. An additional scalar had to be introduced in the reanalysis of the reaction $J/\psi(1S) \rightarrow \gamma 4\pi$ with a mass above 1700 MeV (BUGG 95). According to these investigations, the $f_0(1500)$ decay proceeds dominantly via $\sigma\sigma \rightarrow 4\pi$, where σ denotes the $\pi\pi$ S wave below the $\overline{K}K$ threshold. The $\overline{K}K$ decay of $f_0(1500)$ is suppressed (ABELE 98).

The determination of the $\pi\pi$ coupling of $f_0(1370)$ is aggravated by the strong overlap with the broad background from the $f_0(400–1200)$. Since it does not show up prominently in the 2π spectra, its mass and width are difficult to determine. As mentioned under the $I = 1$ states section, data on $\pi\pi \rightarrow \overline{K}K$ show an enhancement in the scalar partial wave at around 1300 MeV (WETZEL 76, COHEN 80, POLYCHRONAKOS 79, COSTA 80, and LONGACRE 86). According to the phase shift, the resonance is found at about 1400 MeV (COHEN 80), while a reanalysis (BUGG 96) claims a trend towards lower mass. The recent three-channel approach (KAMINSKI 99) supports the Crystal Barrel findings, and yields a broad $f_0(1370)$ with a mass above 1400 MeV and a narrow $f_0(1500)$. Here, the $f_0(1370)$ couples more strongly to $\pi\pi$ than to $\overline{K}K$. The $f_0(1370)$ appears explicitly as $\eta\eta$ resonance in the $\pi^0\eta\eta$ final state of the $\overline{p}p$ annihilation at rest (AMSLER 95D). Further information about the $\overline{K}K$ decay of scalars are most welcome, in particular those that can clearly distinguish the $I = 0$ from the $I = 1$ system.

For numerical estimates of coupling constants of the lightest scalars to two pseudoscalars, see ACHASOV 89E,G,I, KAMINSKI 99, AKHMETSHIN 99C. For example, from these estimates, the $f_0(980)$ coupling to $K\overline{K}$ is much larger than its coupling to $\pi\pi$, which is an important constraint to model builders.

Interpretation: Almost every model on scalar states agrees that the $K^*(1430)$ is the quark model $s\overline{u}$ or $s\overline{d}$ state.

If one uses the naive quark model (which may be too naive because of lack of chiral symmetry constraints), it is natural to assume the $f_0(1370)$, $a_0(1450)$, and the $K^*(1430)$ are in the same SU(3) flavor nonet being the $(\overline{u}u + \overline{d}d)$, $u\overline{d}$ and $u\overline{s}$ state, respectively. In this picture, the choice of the ninth member of the nonet is ambiguous. The controversially discussed candidates are $f_0(1500)$ and $f_0(1710)$ (assuming $J = 0$). Compared to the above states, the $f_0(1500)$ is very narrow. Thus, it is unlikely to be their isoscalar partner. It is also too light to be the first radial excitation. Allowing for a gluonic admixture, one can come to an arrangement among these states. See our note on "Non-$\overline{q}q$ states."

The $f_0(980)$ and $a_0(980)$ are often interpreted as being multiquark states (JAFFE 77), $\overline{K}K$ bound states (WEINSTEIN 90), or vacuum scalars (CLOSE 93A). These pictures are supported by the two-photon widths of these states, which are smaller than expected for naive $\overline{q}q$ mesons neglecting the large $\overline{K}K$ components in the wave function (BARNES 85, LI 91). The results from SND (ACHASOV 98I) reveal a much higher branching ratio for radiative $\phi \to \gamma f_0$ decays than expected for naive $\overline{q}q$ mesons, but also for $\overline{K}K$ molecules (CLOSE 93B).

On the other hand, the states $f_0(980)$ and $a_0(980)$ may form a low-mass state nonet with the σ as a central ingredient, and the $K^*(1430)$ (or "$\kappa(900)$"). Attempts have been made to start directly from chiral symmetry or chiral Lagrangians (SCADRON 99, OLLER 98, 99, HANNAH 99, IGI 99, ISHIDA 99, and TORNQVIST 99), which all predict the existence of the σ meson near 500 MeV. Hence, *e.g.*, in the chiral linear sigma model, the σ is the $(\overline{u}u+\overline{d}d)$ state, and at the same time, also the chiral partner of the π. Hence, an experimental proof of its existence has become very important.

In the unitarized quark model with coupled channels, six of the light scalars are understood as different manifestations of bare quark model $\overline{q}q$ states (TORNQVIST 82,95,96, BEVEREN 86). The σ, $f_0(980)$, $f_0(1370)$, $a_0(980)$, $a_0(1450)$, and $K^*(1430)$ are described as unitarized remnants of strongly shifted and mixed $\overline{q}q$ 1^3P_0 states using six parameters. The $f_0(980)$ and $f_0(1370)$, as well as $a_0(980)$ and $a_0(1450)$, are two manifestations of the same $\overline{q}q$ state.

QCD sum rule techniques (ELIAS 99) generally find that the lightest scalars are nearly decoupled from $q\overline{q}$, which would suggest a non-$q\overline{q}$ structure. But this is also consistent with them being unitarized remnants of $q\overline{q}$ surrounded by large "clouds" of light mesons (forming part of the $q\overline{q}$ sea).

Other detailed models exist, which arrive at different groupings of the observed resonances. Further publications discussing the light scalar resonances are (see also our previous issues): AU 87, MORGAN 93, ZOU 94B, JANSSEN 95, KLEMPT 95, ANISOVICH 98, LOCHER 98, ACHASOV 98D, NARISON 98, and MINKOWSKI 99.