SCALAR MESONS

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I. Introduction: In contrast to the vector and tensor mesons, the identification of the scalar mesons is a long-standing puzzle. Scalar resonances are difficult to resolve because of their large decay widths, which cause a strong overlap between resonances and background, and also because several decay channels open up within a short mass interval. In addition, the $\overline{K}K$ and $\eta\eta$ thresholds in particular produce 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. The number of experimental and theoretical publications since our last issue indicates great activity in this field.

Scalars are produced, for example, in πN scattering on polarized/unpolarized targets, $\overline{p}p$ annihilation (high statistics), central hadronic production, $J/\psi(1S)$ 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.). A least-biased procedure is the energy-independent extraction of partial-wave amplitudes (moment analysis), whereas the dynamical content of an amplitude is modeled in a second step.

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 narrow 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 $f_0(600)$, $f_0(980)$, $f_0(1370)$, 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.

II. The $I = 1/2$ States: The $K^*(1430)$ (ASTON 88) is perhaps the least controversial of the light scalar mesons. The $K\pi$ S-wave scattering has two possible isospin channels, $I = \frac{1}{2}$ and $I = \frac{3}{2}$. The $I = \frac{3}{2}$ wave is elastic and repulsive up to 1.7 GeV (ESTABROOKS 78) and contains no known resonances. The $I = \frac{1}{2}$ $K\pi$ phase shift, measured from about 100 MeV above threshold on, rises smoothly, passes 90° at 1350 MeV, and continues to rise to about 170° at 1600 MeV. The first important inelastic threshold is $K\eta'(958)$. In the inelastic region, the continuation of the amplitude is uncertain since the partial-wave decomposition has several solutions. The data are extrapolated towards the $K\pi$ threshold using effective range-type formulas (ASTON 88, ABELE 98) or chiral perturbation predictions (JAMIN 00, CHERRY 01). In analyses using unitarized amplitudes, there is agreement on the presence of a resonance pole around 1410 MeV having a width of about 300 MeV. In recent years, there has been controversy about the existence of a light and very broad "κ" meson in the 700–900 MeV region. Some authors find this pole in their phenomenological analysis (*e.g.*, ISHIDA 97B, BLACK 98,01, DELBOURGO 98, OLLER 99,99C, BEVEREN 99, ANISOVICH 97C, JAMIN 00, SHAKIN 01), while others, in particular CHERRY 01, KOPP 01 do not. Since it appears to be a very wide object ($\Gamma \approx 600$ MeV) near threshold, its presence and properties are difficult to establish on data.

III. The $I = 1$ States: Two isovector states are known, the established $a_0(980)$ and the $a_0(1450)$. Independent of any model, the $\overline{K}K$ component in the $a_0(980)$-wave function must be large: it lies just below 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 is necessary. In all measurements in our Listings, the mass position agrees on a value near 984 MeV, but the width takes values between 50 and 300 MeV, due to the different applied models. For example, the analysis of the $\overline{p}p$-annihilation data using a unitary K-matrix description finds a width as determined from the T-matrix pole of 92 ± 8 MeV, while the observed width of the peak in the $\pi\eta$ mass spectrum is about 45 MeV.

The relative coupling $\overline{K}K/\pi\eta$ is determined indirectly from $f_1(1285)$ (BARBERIS 98C, CORDEN 78, DEFOIX 72) or $\eta(1440)$ decays (BAI 90C, BOLTON 92B, AMSLER 95C), from the line shape observed in the $\pi\eta$ decay mode (FLATTE 76, AMSLER 94D, BUGG 94, JANSSEN 95), or from the coupled-channel analysis of $\pi\pi\eta$ and $\overline{K}K\pi$ final states of $\overline{p}p$ annihilation at rest (ABELE 98).

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 observation of a broad structure at about 1300 MeV in $\pi N \to \overline{K}KN$ reactions needs further confirmation in its existence and isospin assignment.

The IV. $I = 0$ 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. Analyses based on several different production processes conclude that probably 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 $f_0(600)$, $f_0(980)$, $f_0(1370)$, 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 25 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 $\pi\pi \to \overline{K}K$ cross sections (WETZEL 76, POLYCHRONAKOS 79, COHEN 80, and ETKIN 82B) may have large uncertainties. The πN data (GRAYER 74, BECKER 79) have been analyzed in combination with high-statistics data from $\overline{p}p$ annihilation at rest (see entries labeled as RVUE for reanalyzes of the data). The re-analysis (KAMINSKI 97) finds two out of four relevant solutions, 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.

The suggestion (SVEC 97) of the existence of a narrow f_0 state near 750 MeV, with a small width of 100 to 200 MeV, is excluded by unitarity as shown by (KAMINSKI 97,00), using both the π- and $a_1(1260)$-exchange in the reaction amplitudes. Also, the $2\pi^0$ invariant mass spectra of the $\overline{p}p$ annihilation at rest (AMSLER 95D, 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) resonance called σ. The σ is difficult to establish because of its large width. In addition, it is distorted by a large destructive background from a contact term (or by a derivative coupling) as required by chiral symmetry, crossed channel exchanges, the $f_0(1370)$, and other dynamical features. However, most analyzes listed in our issue under $f_0(600)$ agree on a pole position near $500 - i\,250$ MeV.

The $f_0(980)$ overlaps strongly with this broad background. This can lead 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 $\pi^- p \to \pi^0\pi^0 n$ (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 that is 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 96,98). Due to its interference with the $f_0(1370)$ (and $f_0(1710)$), the peak attributed to $f_0(1500)$ can appear shifted in invariant mass spectra. Therefore, the application of simple Breit-Wigner forms arrives at slightly different resonance masses for $f_0(1500)$. Recent analyses of central-production data of the five decay modes (BARBERIS 99D, BARBERIS 00E) agree on the description of the S wave with the one above. The $\overline{p}p$, $\overline{n}p/\overline{p}n$ (GASPERO 93, ADAMO 93, AMSLER 94, ABELE 96) show a single enhancement at 1400 MeV in the invariant 4π mass spectra, which is resolved into $f_0(1370)$ and $f_0(1500)$ (ABELE 01,01B). The data on 4π from central production (BARBERIS 00C) require both resonances, too, but disagree on the relative content of $\rho\rho$ and $\sigma\sigma$ in 4π. All investigations agree that the 4π decay mode represents about half of the $f_0(1500)$ decay width and is dominant for $f_0(1370)$.

The determination of the $\pi\pi$ coupling of $f_0(1370)$ is aggravated by the strong overlap with the broad $f_0(600)$ and $f_0(1500)$. Since it does not show up prominently in the 2π spectra, its mass and width are difficult to determine. The three-channel approach (KAMINSKI 99) supports the Crystal Barrel findings, and yields a broad $f_0(1370)$ with a mass around 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 $f_0(1370)$ is identified as $\eta\eta$ resonance in the $\pi^0\eta\eta$ final state of the $\overline{p}p$ annihilation at rest (AMSLER 95D).

V. 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 that the $f_0(1370)$, $a_0(1450)$, and the $K^*(1430)$ are in the same SU(3) flavor nonet, which is 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. Assuming the three f_0's in the 1300–1700 region to be mixtures between an $u\overline{u}$, an $s\overline{s}$, and a gluonium state, one can reach an understanding of these states, although different analyses (CLOSE 01B, LI 01) do not agree in detail. See our Note on "Non-$\overline{q}q$ States."

The $f_0(980)$ and $a_0(980)$ are often interpreted as multiquark states (JAFFE 77, ALFORD 00), $\overline{K}K$-bound states (WEINSTEIN 90), or vacuum scalars (CLOSE 93A), excluding them from the scalar nonet. The insight into their internal structure using two-photon widths (BARNES 85, LI 91, DELBOURGO 99, LUCIO 99, ACHASOV 00H) is not conclusive. Based on D_s decays, DEANDREA 01 suggests the $f_0(980)$ is an $\overline{s}s$ surrounded by a virtual $\overline{K}K$ cloud. The results from SND and CMD2 (ACHASOV 00H and AKHMETSHIN 99B) reveal a much higher branching ratio for radiative $\phi \to \gamma f_0/a_0$ decays than expected for $\overline{q}q$ mesons, but also for $\overline{K}K$ molecules (CLOSE 93B, FAZIO 01). On the other hand, the states $f_0(980)$ and $a_0(980)$ may form a new low-mass state nonet together with the $f_0(600)$ as a central ingredient, plus the κ. The $f_0(980)$ and $a_0(980)$ inclusive production properties in hadronic Z^0 decays are consistent with mesons of other nonets (ACKERSTAFF 98A,98Q, ABREU 99J).

Attempts have been made to start directly from chiral Lagrangians (SCADRON 99, OLLER 99, ISHIDA 99, and TORNQVIST 99) which predict the existence of the σ meson near 500 MeV. Hence, *e.g.*, in the chiral linear sigma model with 3 flavors, the σ, $a_0(980)$, $f_0(980)$, and κ (or $K_0^*(1430)$) would form a nonet (not necessarily $\overline{q}q$), while the lightest pseudoscalars would be their chiral partners. In the approach of OLLER 99, the above resonances are generated starting from chiral perturbation theory predictions near the first open channel, and then by extending the predictions to the resonance regions using unitarity.

In unitarized quark models with coupled channels, six of the light scalars are understood as different manifestations of bare, nearly degenerate, nonet states (TORNQVIST 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 states derived from the original bare states. The $f_0(980)$ and $f_0(1370)$, as well as $a_0(980)$ and $a_0(1450)$, are two manifestations (one $\overline{q}q$ and one meson-meson) of the same bare input state.

QCD sum-rule techniques (FANG 00) generally find that the lightest scalars are nearly decoupled from $\overline{q}q$, which would suggest a non-$\overline{q}q$ structure. But this is also consistent with their being unitarized remnants of $\overline{q}q$ surrounded by large "clouds" of light mesons (forming part of the $\overline{q}q$ sea).

Other detailed models exist, which arrive at different groupings of the observed resonances.

References

References may be found at the end of the $f_0(600)$ Listing.