NOTE ON 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 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, central hadronic production, J/ψ, B-, 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 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 $(I = 1/2)$ a possible $K_0^*(800)$ (or κ), which need to be confirmed, the $K_0^*(1430)$, $(I = 1)$ $a_0(980)$,

$a_0(1450)$, and ($I = 0$) $f_0(600)$ or σ, $f_0(980)$, $f_0(1370)$, 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 $K_0^*(1430)$ (ASTON 88) is perhaps the least controversial of the light scalar mesons. The $K\pi$ S-wave scattering has two possible isospin channels, $I = 1/2$ and $I = 3/2$. The $I = 3/2$ wave is elastic and repulsive up to 1.7 GeV (ESTABROOKS 78) and contains no known resonances. The $I = 1/2$ $K\pi$ 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 (*e.g.*, D-meson decay analyses LINK 02E, AITALA 02). Some authors find this pole in their phenomenological analysis (see *e.g.*, ISHIDA 97B,03, BLACK 01 03, DELBOURGO 98, OLLER 99,99C, ANISOVICH 97C, JAMIN 00, SHAKIN 01, SCADRON 03), while others do not (*e.g.*, CHERRY 01, KOPP 01). Since it appears to be a very wide object ($\Gamma \approx 400$ 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, mostly due to the different models. For example, the analysis of the $\overline{p}p$-annihilation data using an 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 $\eta(1410)$ 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 in $\overline{p}p$ annihilation experiments with stopped and higher momenta $\overline{p}$, with a mass of about 1450 MeV, or close to the $a_2(1320)$ meson, which is typically a dominant feature. The relative couplings to the final states $\pi\eta$, $\overline{K}K$, and $\pi\eta'(958)$ are close to SU(3)-flavor predictions for an ordinary $\overline{q}q$ meson. The broad structure at about 1300 MeV observed in $\pi N \to \overline{K}KN$ reactions needs further confirmation in its existence and isospin assignment.

IV. 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. Analyses based on several different production processes conclude that probably four poles are needed in the mass range from $\pi\pi$ 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 more than 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 re-analyses of the data). The re-analysis (KAMINSKI 97, see also KAMINSKI 02, 03) 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^o (in the "up") or 140^o (in the "down") solution to reach 230^o, 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, 02, 03), 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 distinct resonance structure below 900 MeV, and these data are consistently described with the standard "down" solution, which allows for the existence of the broad ($\Gamma \approx 500$ MeV) resonance called σ. The σ pole is difficult to establish because of its large width, and can certainly not be modelled by a naive Breit-Wigner resonance. It can be distorted by a large destructive background required by chiral symmetry, and from crossed channel exchanges, the $f_0(1370)$, and other dynamical features. However, most analyses 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 the σ and the above mentioned 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, and ABELE 98). Due to its interference with the $f_0(1370)$ (and $f_0(1700)$), the peak attributed to $f_0(1500)$ can appear shifted in invariant mass spectra. Therefore, the application of simple Breit-Wigner forms arrive at slightly different resonance masses for $f_0(1500)$. Analyses of central-production data of the likewise five decay modes (BABERIS 99D, BABERIS 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, ABELE 01B). The data on 4π from central production (BABERIS 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 findings in $\overline{p}p$ annihilation, 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 What is the nature of the light scalars? In the literature, many suggestions are discussed in the literature such as $q\overline{q}$, $q\overline{q}q\overline{q}$ or meson-meson bound states supplemented with a scalar glueball. In reality, they are superpositions of these components, and one depends on models to determine the dominant component. Although we have seen progress in recent years, this question remains open. Here, we mention some of the present conclusions.

Almost every model on scalar states agrees that the $K_0^*(1430)$ is predominantly 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 $K_0^*(1430)$ 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 $f_J(1720)$ (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 MeV region to be mixtures between an $\overline{u}u$, $\overline{s}s$, and a gluonium state, one can arrive at an arrangement 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) or $\overline{K}K$ bound states (WEINSTEIN 90). 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 that the $f_0(980)$ is mainly $\overline{s}s$ surrounded by a virtual $\overline{K}K$ cloud. Recent data on radiative decays ($\phi \to f_0\gamma$ and $\phi \to a_0\gamma$) from SND (ACHASOV 00F, ACHASOV 00H), CMD2 (AKHETSHIN 99C), and KLOE (ALOISIO 02C, ALOISIO 02D) favor a 4-quark picture of the $f_0(980)$ and $a_0(980)$. (This conclusion may, however, be due to an oversimplified model for the radiative decays (BOGLIONE 03, OLLER 03B).) But it remains quite possible that the states $f_0(980)$ and $a_0(980)$, together with the $f_0(600)$ and the κ, may form a new nonet of predominantly four-quark states. This light scalar nonet has also been suggested (CLOSE02B) to consist of a central core of mainly four quarks, like those suggested by JAFFE 77, to make up a flavour nonet composed of four quarks in a particular colour configuration. At larger distances, the quarks would recombine into a pair of color singlet $q\overline{q}$'s, forming finally two pseudoscalars mesons and a meson cloud at the periphery.

Attempts have been made to start directly from chiral Lagrangians (SCADRON 99, OLLER 99, ISHIDA 99, and TORNQVIST 99, OLLER 03B), 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 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 $q\overline{q}$ and meson-meson channels, the light scalars can be understood as additional manifestations of bare $q\overline{q}$ confinement states, originally in the 1.3–1.5 GeV region, but very distorted and shifted due to the strong ${}^3P_0$ coupling to S-wave two-meson decay channels (TORNQVIST 95,96, BEVEREN 86,99,01B). Thus, the light scalar nonet comprising the $f_0(600)$ (σ), $f_0(980)$, $K_0^*(800)$ (κ), and $a_0(980)$, as well as the regular nonet consisting of the $f_0(1370)$, $f_0(1500)$ (or $f_0(1710)$), $K_0^*(1430)$, and $a_0(1450)$, respectively, are two manifestations of the same bare input states (see also BOGLIONE 02).

Other models with different groupings of the observed resonances do of course exist. See *e.g.*, earlier versions of this review and papers listed as other related papers below.

References

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