NOTE ON SCALAR MESONS

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In contrast to the vector and tensor mesons the identification of the scalar mesons is a long standing puzzle. The problem originates from their large decay widths causing a strong overlap of individual resonances within the same partial wave, and at the same time several decay channels open up within a short mass interval. In addition the $K\overline{K}$ and $\eta\eta$ thresholds produce sharp cusps in the energy dependence of the resonant amplitude. Furthermore, one expects non-$q\overline{q}$ scalar objects like glueballs and multiquark states in the mass range below 1800 MeV. In spite of these problems the understanding of the scalars has improved considerably during the last few years, because we now have high statistics measurements of different production modes from: $p\overline{p}$ annihilation at rest, πN-scattering on polarized/unpolarized targets, central production, $J/\psi(1S)$ decays, D-meson decays, $\gamma\gamma$-formation. Furthermore, we have had a strong development of better theoretical models for the reaction amplitudes, which are based on common fundamental principles. These allow direct comparison and interpretation of many different experimental results. Two-body unitarity, analyticity, Lorentz invariance, chiral- and flavor-symmetry constraints have been implemented into the transition amplitudes using different general methods (K-matrix formalism, N/D-method, Dalitz-Tuan ansatz, unitarized quark models with coupled channels, *etc.*). In general, mass and width parameters of a resonance are found from the position of the nearest pole in the T-matrix (or equivalently 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 a naive Breit-Wigner parametrization (or K-matrix pole parametrization) agree approximately with the T-matrix pole position in the amplitude. Breit-Wigner parameters are sensitive to background, nearby thresholds *etc.*, while T-matrix poles depend only on the limitations of the theoretical model.

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In this note we discuss all light scalars organized in the listings under the entries ($I = 1/2$) $K_0^*(1430)$, ($I = 1$) $a_0(980)$, $a_0(1450)$, and ($I = 0$) σ or $f_0(400\text{–}1200)$, $f_0(980)$, $f_0(1370)$, and $f_0(1500)$. The list is minimal and does not necessarily exhaust the list of actual resonances.

The $\boldsymbol{I = 1/2}$ *states*

The $K_0^*(1430)$ (ASTON 88) is the least controversial of the light scalar mesons. The phase shift rises smoothly from threshold, passes 90° at 1350 MeV, and then continues to rise to about 170° at 1600 MeV at the first important inelastic threshold $K\eta'(958)$. Thus it behaves like a single broad, nearly elastic resonance. ABELE 98 finds for the T-matrix pole parameters, $m \approx 1430$ MeV and $\Gamma \approx 290$ MeV, while the K-matrix pole of the same data is at about 1340 MeV using $K\overline{K}\pi$ in $p\overline{p}$ annihilation at rest. This agrees with the LASS (ASTON 88) determination. The scattering length near threshold is $a = 2.56 \pm 0.20$ (GeV/c)$^{-1}$ (ABELE 98).

The $\boldsymbol{I = 1}$ *states*

Two states are established, the well-known $a_0(980)$, and the $a_0(1450)$ found by Crystal Barrel (AMSLER 94D). Independently of any model about the nature of the $a_0(980)$ the $K\overline{K}$ component in the wave function of the state must be large: the $a_0(980)$ lies very close to the opening of the $K\overline{K}$ channel to which it couples strongly. This gives an important cusp-like behaviour 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. A naive Breit-Wigner form is certainly inadequate.

The relative coupling $K\overline{K}/\pi\eta$ in previous editions was determined only indirectly from $f_1(1285)$ (CORDEN 78, DEFOIX 72) or $\eta(1410)$ decays (BAI 90C, BOLTON 92B, AMSLER 95F) or from the line shape observed in the $\pi\eta$ decay mode (FLATTE 76, AMSLER 94D, BUGG 94, JANSSEN 95). From analysis of $\pi\pi\eta$ and $K\overline{K}\pi$ final states of $\overline{p}p$ annihilation at rest a relative production ratio $\mathrm{B}(\overline{p}p \to \pi a_0; a_0 \to K\overline{K}) / \mathrm{B}(\overline{p}p \to \pi a_0; a_0 \to \pi\eta) = 0.23 \pm 0.05$ 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 $\Gamma(K\overline{K})/\Gamma(\pi\eta)$=1.03 ± 0.14. Analysis of $p\overline{p}$ 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 our table the mass position comes out very consistently near 980 MeV in all measurements, but the width takes values between 50 and 300 MeV, because of the differences in the models used in the analyses. Using the relative production ratio and the observed 2-photon generation of $a_0(980)$ one can calculate the 2-photon width of $a_0(980)$ to be $\Gamma_{\gamma\gamma} = (0.30 \pm 0.10)$ keV, which is similar to that of $f_0(980)$.

The $a_0(1450)$ is seen by the Crystal Barrel experiment in its $\pi\eta$, $K\overline{K}$, 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 $q\overline{q}$ meson.

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 $\pi\pi$, $K\overline{K}$, $\eta\eta$, 4π, and $\eta\eta'(958)$ systems produced in S-waves by nonstrange initial states. From the high statistics data sets collected from $\overline{p}p$ annihilation at rest into $\pi^0 f_0$'s, where the f_0 decay into the above mentioned channels, one concludes that at least four poles are needed in the mass range from $\pi\pi$ threshold to about 1600 MeV. The claimed isoscalar resonances are found under the 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 $\pi\pi$ and $K\overline{K}$ final states. Information on the $\pi\pi$ S-wave phase shift $\delta^I_J = \delta^0_0$ was extracted already 20 years ago from πN scattering with unpolarized (GRAYER 74) and polarized target (BECKER 79) and near threshold from K_{e4}-decay (ROSSELET 77). The $\pi\pi$ S-wave inelasticity is not accurately known, and the reported $\pi\pi \to K\overline{K}$ cross sections (WETZEL 76, POLYCHRONAKOS 79, COHEN 80, ETKIN 82B) may have large uncertainties. Recently, the πN data (GRAYER 74, BECKER 79) have been reevaluated in a combined partial-wave analysis (KAMINSKI 97). Out of four, two relevant solutions are found with the S-wave phase-shift rising slower than the P-wave [$\rho(770)$], which is used as 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 800-980 MeV. Both solutions exhibit at 1 GeV a sudden drop in the modulus and in the inelasticity parameter η_0^0, which is due to the appearance of $f_0(980)$ very close to the opening of the $K\overline{K}$-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°, from which point both continue to rise slowly.

SVEC 97 using data on πN(polarized) producing the $\pi\pi$ system from 600 to 900 MeV suggests that there exists a narrow state at 750 MeV with a small width of 100 to 200 MeV. Such a solution is also found by (KAMINSKI 97) using the CERN-Munich(-Cracow) data considering both 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 seems to be excluded. Also, the $2\pi^0$ invariant mass spectra of $p\overline{p}$ annihilation at rest (AMSLER 95B, ABELE 96) and 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 $f_0(400\text{–}1200)$.

For low-energy $\pi\pi$ scattering the predicted Weinberg scattering length for the isoscalar S-wave a_0^0 is 0.16, chiral perturbation theory including one-loop corrections increases this value to $a_0^0 \approx 0.20$ while the slope parameter is $b_0^0 \approx 0.18$ (GASSER 83, RIGGENBACH 91). With two-loop corrections one still gets a little larger value $a_0^0 = 0.217$ (BIJNENS 96), but electromagnetic corrections reduce this value to 0.208 (MALTMAN 97). Experimentally the region near the $\pi\pi$ threshold is difficult to investigate. Current values of these quantities are $a_0^0 = 0.26 \pm 0.05$ and $b_0^0 = 0.25 \pm 0.03$ (NAGELS 79).

An experimentally very well studied meson resonance is the $f_0(1500)$ seen by the Crystal Barrel experiment in five decay modes: $\pi\pi$, $K\overline{K}$, $\eta\eta$, $\eta\eta'(958)$, and 4π (AMSLER 95D, ABELE 96, 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. They applied a sum of Breit-Wigner functions for the dynamics in the resonant amplitude. In central production (ANTINORI 95) a peak at 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, ABELE 96). In the $5\pi^0$ channel (ABELE 96) this structure was resolved into $f_0(1500)$ and $f_0(1370)$, found at a somewhat lower mass around 1300 MeV. An additional scalar in mass above 1700 MeV had to be introduced in the re-analysis of the reaction $J/\psi(1S) \rightarrow \gamma 4\pi$ (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 $K\overline{K}$ threshold. The $K\overline{K}$ decay of $f_0(1500)$ is suppressed (ABELE 98).

The determination of the $\pi\pi$ coupling of $f_0(1370)$ is inhibited by the strong overlap with the broad background from the $f_0(400\text{–}1200)$. Since it does not show up prominently in the 2π spectra its mass and width are difficult to fix. A resonance band in the $\pi^0\eta\eta$ final state of $p\overline{p}$ annihilation at rest (AMSLER 95D) is attributed to it. Data on $\pi\pi \rightarrow K\overline{K}$ show an enhancement at around 1300 MeV in the scalar partial wave (WETZEL 76, COHEN 80, POLYCHRONAKOS 79, COSTA 80, LONGACRE 86). According to the phase shift the resonance is found around 1400 MeV (COHEN 80), while a recent re-analysis (BUGG 96) claims a trend to lower mass. Further information about the $K\overline{K}$ decay of the scalars are most welcome, in particular those which clearly distinguish between the $I = 0$ and the $I = 1$ system.

In the analysis of (ANISOVICH 97, 97C) using data of πN and $\overline{p}p$ annihilation reactions a fifth pole at 1530 MeV about 1 GeV off the physical region is added.

Interpretation

Almost every model on the scalar states agrees that the $K_0^\star(1430)$ is the $1\,^3P_0$ quark model $s\overline{u}$ or $s\overline{d}$ state, but the other scalars remain controversial.

The $f_0(980)$ and $a_0(980)$ are often interpreted as being multiquark states (JAFFE 77) or $K\overline{K}$ bound states (WEINSTEIN 90). This picture is supported by their 2-photon widths which are smaller than expected for $q\overline{q}$ mesons, if one neglects the $K\overline{K}$ component. Using a simple quark model one is led to put the $f_0(1370)$, $a_0(1450)$, and $K_0^\star(1430)$ into the same SU(3) flavor nonet being the $(u\overline{u}+d\overline{d})$, $u\overline{d}$ and the $u\overline{s}$ state, respectively. In this picture the $s\overline{s}$ state is missing experimentally. Compared with these states the $f_0(1500)$ is too narrow to be the isoscalar partner, and too light to be the first radial excitation. A non-$q\overline{q}$ (gluonium) interpretation seems likely (CLOSE 97B). See our Note on Non-$q\overline{q}$ states. As to the light $f_0(400–1200)$ structure it is far from the physical region and its interpretation in terms of a $q\overline{q}$ state or cross channel effect remains open. Such a state is often referred to as the σ or $f_0(500)$ meson.

More detailed models exist, which include more theoretical input at least phenomenologically. One such unitarized quark model with coupled channels can understand 6 of the light scalars as different unitarized manifestations of bare quarks model $^3P_0$ $q\overline{q}$ states (TORNQVIST 82, 95, 96). The σ, $f_0(980)$, $f_0(1370)$, $a_0(980)$, $a_0(1450)$, and $K_0^\star(1430)$ are described as unitarized remnants of strongly shifted and mixed $q\overline{q}$ $1\,^3P_0$ states using 6 parameters. Here the σ is the $(u\overline{u}+d\overline{d})$ state and at the same time also the chiral partner of the π. The $f_0(980)$ and $f_0(1370)$ as well as $a_0(980)$ and $a_0(1450)$ are two manifestations of the same $q\overline{q}$ state. The interpretation of $f_0(1500)$ in this scheme is an open question; it can be a glueball or a deuteron-like $\rho\rho+\omega\omega$ bound state. For other models and more details discussing the light scalar resonances see also (AU 87, MORGAN 93, ZOU 94B, JANSSEN 95, CLOSE 92, ANISOVICH 97, 97B, 97C, 97D, BEVEREN 86, KAMINSKI 94, 97B, OLLER 97, ISHIDA 96).