NOTE ON SCALAR MESONS

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I. Introduction:

The scalar mesons are especially important to understand because they have the same quantum numbers as the vacuum ($J^{PC} = 0^{++}$). Therefore they can condense into the vacuum and break a symmetry like a global chiral $U(N_f) \times U(N_f)$. The details of how this symmetry breaking is implemented in Nature is one of the most profound problems in particle physics.

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 $K\bar{K}$ and $\eta\eta$ thresholds produce sharp cusps in the energy dependence of the resonant amplitude. Furthermore, one expects non-$q\bar{q}$ scalar objects, like glueballs and multiquark states in the mass range below 1800 MeV. For some recent reviews see AMSLER 04, BUGG 04C, CLOSE 02B, and KLEMPT 07.

Scalars are produced, for example, in πN scattering on polarized/unpolarized targets, $p\bar{p}$ 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.*). Dynamics near the lowest two-body thresholds in some analyses is described by crossed channel (t, u) meson exchange or with an effective range parameterization instead of or in addition to resonant features in the s-channel, only. Furthermore, elastic S-wave scattering amplitudes involving soft pions have zeros close to threshold (ADLER 65, 65A),

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which may be shifted or removed in associated production processes.

The mass and width of a resonance are found from the position of the nearest pole in the process amplitude (T-matrix or S-matrix) at an unphysical sheet of the complex energy plane: $(E - i\,\Gamma/2)$. It is important to notice 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 this pole position.

In this note, we discuss all light scalars organized in the listings under the entries $(I = 1/2)$ $K_0^*(800)$ (or κ), $K_0^*(1430)$, $(I = 1)$ $a_0(980)$, $a_0(1450)$, 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 in Kp production, 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 (BERNARD 91, 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. With reduced model dependence (LINK 07) finds a larger width of 500 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. Hadronic D-meson decays provide additional data points in the vicinity of the $K\pi$ threshold - experimental results from E791 (*e.g.* AITALA 02, 06), FOCUS (LINK 02, 07), CLEO (CAWLFIELD 06A), and BaBar (AUBERT 07T) are discussed in the *Review of Charm Dalitz Plot Analyses*. Precision information from semileptonic D decays avoiding theoretically ambiguous three-body final state interactions is not available. BES II finds a κ like structure in J/ψ decays to $\bar{K}^{*0}(892)K^+\pi^-$ where κ recoils against the $K^*(892)$ (ABLIKIM 06C, re-analyzed by (GUO 06)). Also clean with respect to final state interaction is the decay $\tau^- \to K_S^0\pi^-\nu_\tau$ studied by Belle (EPIFANOV 07), with $K^*(800)$ parameters fixed to (ABLIKIM 06C).

Some authors find a κ pole in their phenomenological analysis (see *e.g.* ANISOVICH 97C, DELBOURGO 98, OLLER 99, 99C, JAMIN 00, SHAKIN 01, SCADRON 03, BLACK 01,03, BUGG 03, ISHIDA 03, ZHENG 04, PALAEZ 04A, ZHOU 06, CAWLFIELD 06A, LINK 07B), while others do not (*e.g.* AUBERT 07T, LINK 02E, 05I, CHERRY 01, KOPP 01). Since it appears to be a very wide object ($\Gamma \approx 500$ MeV) near the $K\pi$ threshold, its presence and properties have been difficult to establish.

Recently a pole position for the κ was found in a theoretical analysis by DESCOTES-GENON 06 in the $K\pi \to K\pi$ amplitude on the second sheet. Their analysis involves the Mandelstam representation, which includes unitarity, analyticity and crossing symmetry. The precise position of the pole should be confirmed by independent analyses and different experiments.

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 $K\bar{K}$ component in the $a_0(980)$ wave function must be large: it lies just below the opening of the $K\bar{K}$ channel to which it strongly couples. This generates 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 100 MeV, mostly due to the different models. For example, the analysis of the $p\bar{p}$-annihilation data (ABELE 98) 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 $K\bar{K}/\pi\eta$ 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 $K\bar{K}\pi$ final states of $p\bar{p}$ annihilation at rest (ABELE 98).

The $a_0(1450)$ is seen in $p\bar{p}$ annihilation experiments with stopped and higher momenta $\bar{p}$, with a mass of about 1450 MeV or close to the $a_2(1320)$ meson which is typically a dominant feature. The broad structure at about 1300 MeV observed in $\pi N \to K\bar{K}N$ reactions (MARTIN 79) 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 $\pi\pi$, $K\bar{K}$, $\eta\eta$, 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 $f_0(1500)$.

For discussions of the $\pi\pi$ S wave below the $K\bar{K}$ threshold and on the long history of the $\sigma(600)$, which was suggested in linear sigma models about 50 years ago, see our reviews in previous editions and the conference proceedings KYOTO 00.

Information on the $\pi\pi$ S-wave phase shift $\delta^I_J = \delta^0_0$ was already extracted 30 years ago from the πN scattering (GRAYER 74, BECKER 79), and near threshold from the K_{e4}-decay (ROSSELET 77). The reported $\pi\pi \to K\bar{K}$ cross sections

(WETZEL 76, POLYCHRONAKOS 79, COHEN 80, and ETKIN 82B) have large uncertainties. Recently, the πN data have been analyzed in combination with high-statistics data (see entries labeled as RVUE for re-analyses of the data). The $2\pi^0$ invariant mass spectra of the $p\bar{p}$ annihilation at rest (AMSLER 95D, ABELE 96) and the central collision (ALDE 97) do not show a distinct resonance structure below 900 MeV, but these data are consistently described with the standard solution for πN data (GRAYER 74, KAMINSKI 97), which allows for the existence of the broad σ. An enhancement is observed in the $\pi^+\pi^-$ invariant mass near threshold in the decays $D^+ \rightarrow \pi^+\pi^-\pi^+$ (AITALA 01B, LINK 04, BONVICINI 07) and $J/\psi \rightarrow \omega\pi^+\pi^-$ (AUGUSTIN 89, ABLIKIM 04A), and in $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ with very limited phase space (GALLEGOS 04, ABLIKIM 07A).

The precise σ pole is difficult to establish because of its large width, and because it can certainly not be modelled by a naive Breit-Wigner resonance. It is distorted by background as required by chiral symmetry, and from crossed channel exchanges, the $f_0(1370)$, and other dynamical features. However, most of the analyzes under $f_0(600)$ listed in our previous issues agree on a pole position near $(500 - i\,250$ MeV).

The existence of the light and very broad σ resonance in the 500 MeV region has been proposed by many authors for over 10 years. In particular, data analyses that included unitarity, $\pi\pi$ threshold behavior and the chiral symmetry constraints from Adler zeroes and scattering lengths needed the light and broad σ in the $\pi\pi$ data.

A precise pole position with an uncertainty of less than 20 MeV (see our table for T-matrix pole) is derived by CAPRINI 06 using unitarized chiral perturbation theory. An important ingredient is the use of Roy-Steiner equations derived from crossing symmetry, analyticity and unitarity. With these constraints CAPRINI 06 find that their position of the σ pole depends, almost exclusively, only on the value of the isosinglet S-wave phase shift at 800 MeV and the S-wave scattering lengths a_0^0 and a_0^2. Using analyticity and unitarity only to describe data from $K_{2\pi}$ and K_{l4} decays GARCIA-MARTIN 07 find comparable pole position and scattering length a_0^0.

PENNINGTON 06, 07 found that the data for $\sigma \to \gamma\gamma$ are consistent with what is expected for a two step process of $\gamma\gamma \to \pi^+\pi^-$ via pion exchange in the t- and u-channel, followed by a final state interaction $\pi^+\pi^- \to \pi^0\pi^0$. Therefore it may be difficult to learn anything new about the nature of the σ from its $\gamma\gamma$ coupling. There are theoretical indications (*e.g.* PELAEZ 06, CHEN 07A, GIACOSA 07, MAIANI 07) that the σ pole behaves differently from a $q\bar{q}$-state.

The $f_0(980)$ overlaps strongly with the σ and background represented by a very slow varying phase extending to higher masses and/or the $f_0(1370)$. This can lead to a dip in the $\pi\pi$ spectrum at the $K\bar{K}$ 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. The σ, and the $f_0(980)$, are also observed in radiative decays ($\phi \to f_0\gamma$) in SND data (ACHASOV 00F, ACHASOV 00H), CMD2 (AKHMETSHIN 99B), and in KLOE data (ALOISIO 02C, AMBROSINO 07). Analyses of $\gamma\gamma \to \pi\pi$ data (BOGLIONE 99, MORI 07) underline the importance of the $K\bar{K}$ coupling of $f_0(980)$.

The f_0's above 1 GeV. A meson resonance that is very well studied experimentally, is the $f_0(1500)$ seen by the Crystal Barrel experiment in five decay modes: $\pi\pi$, $K\bar{K}$, $\eta\eta$, $\eta\eta'(958)$, and 4π (AMSLER 95D, ABELE 96, and ABELE 98). Due to its interference with the $f_0(1370)$ (and $f_0(1710)$), 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 (BARBERIS 99D, BARBERIS 00E) agree on the description of the S-wave with the one above. The $p\bar{p}$, $p\bar{n}/n\bar{p}$ (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, ABELE01B). 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. Multichannel analyses of hadronically produced two- and three-body final states agree on a mass between 1300 MeV and 1400 MeV and a narrow $f_0(1500)$, but arrive at a somewhat smaller width for $f_0(1370)$.

Both Belle and BaBar have observed strong indications of scalars in B meson decays. They observe a broad structure between 1 and 1.6 GeV in K^+K^- and $\pi^+\pi^-$ decays (GARMASH 02, 06, 07, AUBERT 06O, 07BB). It could be a result of interference of several resonances in this mass range, but lack of statistics prevent from an unambiguous identification of this effect.

V. Interpretation of the scalars below 1 GeV: In the literature, many suggestions are discussed such as conventional $q\bar{q}$ mesons, $q\bar{q}q\bar{q}$ or meson-meson bound states mixed with a scalar glueball. In reality, they can be superpositions of these components, and one depends on models to determine the dominant one. Although we have seen progress in recent years, this question remains open. Here, we mention some of the present conclusions.

If one uses the naive quark model 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 $(u\bar{u} + d\bar{d})$, $u\bar{d}$ and $u\bar{s}$ 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 $f_0(1700)$. 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.

The $f_0(980)$ and $a_0(980)$ are often interpreted as multiquark states (JAFFE 77, ALFORD 00, MAIANI 04A) or $K\bar{K}$ 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. The $f_0(980)$ appears as a peak structure in $J/\psi \rightarrow \phi\pi^+\pi^-$ and in D_s decays without $f_0(600)$ background. Based on that observation it is suggested that $f_0(980)$ has a large $s\bar{s}$ component, which according to (DEANDREA 01) is surrounded by a virtual $K\bar{K}$ cloud. Data on radiative decays ($\phi \rightarrow f_0\gamma$ and $\phi \rightarrow a_0\gamma$) from SND, CMD2, and KLOE (see above) favor a 4-quark picture of the $f_0(980)$ and $a_0(980)$. The underlying model for this conclusion (BOGLIONE 03, OLLER 03B) however may be oversimplified. But it remains quite possible that the states $f_0(980)$ and $a_0(980)$, together with the $f_0(600)$ and the $K_0^*(800)$, form a new low-mass state nonet of predominantly four-quark states, where at larger distances the quarks recombine into a pair of pseudoscalar mesons forming by a meson cloud.

Attempts have been made to start directly from chiral Lagrangians (SCADRON 99, OLLER 99, ISHIDA 99, TORNQVIST 99, OLLER 03B, NAPSUCIALE 04, 04A) 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 $q\bar{q}$), while the lightest pseudoscalars would be their chiral partners.

In such models inspired by the linear sigma model the light $\sigma(600)$ is often referred to as the "Higgs boson of strong interactions", since the σ plays a role similar to the Higgs particle in electro-weak symmetry breaking. It is important for chiral symmetry breaking which generates most of the proton and η' mass, and what is referred to as the constituent quark mass.

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 the unitarized quark model with coupled $q\bar{q}$ and meson-meson channels, the light scalars can be understood as additional manifestations of bare $q\bar{q}$ confinement states, strongly mass shifted from the 1.3 - 1.5 GeV region and very distorted 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 $f_0(600)$, $f_0(980)$, $K_0^*(800)$, and $a_0(980)$, as well as the regular nonet consisting of the $f_0(1370)$, $f_0(1500)$ (or $f_0(1700)$), $K_0^*(1430)$, 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 exist and may *e.g.* be found in earlier versions of this review and papers listed as other related papers below.

VI. Interpretation of the f_0's above 1 GeV: The $f_0(1370)$ and $f_0(1500)$ decay mostly into pions (2π and 4π) while the $f_0(1710)$ decays mainly into $K\bar{K}$ final states. The $K\bar{K}$ decay branching ratio of the $f_0(1500)$ is small (ABELE 96B,98, BARBERIS 99D). Naively, this suggests a $n\bar{n}$ $(= u\bar{u} + d\bar{d})$ structure for the $f_0(1370)$ and $f_0(1500)$, and $s\bar{s}$ for the $f_0(1710)$. The latter is not observed in $p\bar{p}$ annihilation (AMSLER 02), as expected from the OZI suppression for an $s\bar{s}$ state.

However, in $\gamma\gamma$ collisions leading to $K_S^0 K_S^0$ (ACCIARRI 01H) and K^+K^- (ABE 04), a spin 0 signal is observed at the $f_0(1710)$ mass (together with a dominant spin 2 component), while the $f_0(1500)$ is not observed in $\gamma\gamma \to K\bar{K}$ nor $\pi^+\pi^-$ (BARATE 00E). The upper limit from $\pi^+\pi^-$ excludes a large $n\bar{n}$ content, and hence would point to a mainly $s\bar{s}$ content for the $f_0(1500)$ (AMSLER 02B). This appears to contradict the small $K\bar{K}$ decay branching ratio of the $f_0(1500)$ and makes a $q\bar{q}$ assignment difficult for this state. Hence the $f_0(1500)$ could be mainly glue due its absence of 2γ-coupling, while the $f_0(1710)$ coupling to 2γ would be compatible with an $s\bar{s}$ state. However, the 2γ-couplings are sensitive to glue mixing with $q\bar{q}$ (CLOSE 05).

The narrow width of $f_0(1500)$, and its enhanced production at low transverse momentum transfer in central collisions (CLOSE 97,98B, KIRK 00) also favor $f_0(1500)$ to be non-$q\bar{q}$.

In the mixing scheme of CLOSE 05, which uses central production data from WA102 and the recent hadronic J/ψ decay data from BES (ABLIKIM 04E, 05), glue is shared between $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. The $f_0(1370)$ is mainly $n\bar{n}$, the $f_0(1500)$ mainly glue and the $f_0(1710)$ dominantly $s\bar{s}$. This agrees with previous analyses (AMSLER 96, CLOSE 01B), but alternative schemes have been proposed (e.g. LEE 00, MINKOWSKI 99; for a review see *e.g.* AMSLER 04). In particular, for a scalar glueball, the two-gluon coupling to $n\bar{n}$ appears to be suppressed by chiral symmetry (CHANOWITZ 05) and therefore the $K\bar{K}$ decay could be enhanced.

Whether the $f_0(1500)$ is observed in 'gluon rich' radiative J/ψ decays is debatable (ABLIKIM 06V) because of the limited amount of data - more data for this and the $\gamma\gamma$ mode are needed.

References

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