NOTE ON SCALAR MESONS

Updated January 2006 by S. Spanier (University of Tennessee) and N.A. Törnqvist (Helsinki).

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 $\bar{K}K$ and $\eta\eta$ thresholds produce sharp cusps in the energy dependence of the resonant amplitude. Furthermore, one expects non-$\bar{q}q$ 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. For some recent reviews see AMSLER 04, BUGG 04C, CLOSE 02B.

Scalars are produced, for example, in πN scattering on polarized/unpolarized targets, $\bar{p}p$ 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 flavour-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), 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

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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 parametrization) 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), $K^*(1430)$, ($I = 1$) $a_0(980)$, $a_0(1450)$, 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 $K^*(1430)$ (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. 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 02, AITALA 02, 06). Some authors find this pole in their phenomenological analysis (see *e.g.* PALAEZ 04A, ZHENG 04, ISHIDA 03, BLACK 01,03, BUGG 03, DELBOURGO 98, OLLER 99, 99C, SCADRON 03, ANISOVICH 97C, JAMIN 00, SHAKIN 01), while others do not (*e.g.* CHERRY 01, KOPP 01, LINK 05I). Since it appears to be a very wide object ($\Gamma \approx$

500 MeV) near the $K\pi$ threshold, its presence and properties are difficult to establish on data.

In an important observation BES 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).

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 $\bar{K}K$ component in the $a_0(980)$ wave function must be large: it lies just below the opening of the $\bar{K}K$ 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 300 MeV, mostly due to the different models. For example, the analysis of the $\bar{p}p$-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 $\bar{K}K/\pi\eta$ 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 $\bar{K}K\pi$ final states of $\bar{p}p$ annihilation at rest (ABELE 98).

The $a_0(1450)$ is seen in $\bar{p}p$ 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 $\pi N \to \bar{K}KN$ 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 $\pi\pi$, $\bar{K}K$, $\eta\eta$, 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 $\bar{K}K$ final states. 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 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 $\pi\pi \to \bar{K}K$ 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 $\bar{p}p$ annihilation at rest (see entries labeled as RVUE for re-analyses of the data). The re-analysis (KAMINSKI 97, 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 $\bar{K}K$-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. The $2\pi^0$ invariant mass spectra of the $\bar{p}p$ 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 (GRAYER 74, KAMINSKI 97), which allows for the existence of the broad ($\Gamma \approx 500$ MeV) resonance called σ. An enhancement is observed in the $\pi^+\pi^-$

invariant mass near threshold in the decays $D^+ \to \pi^+\pi^-\pi^+$ (AITALA 01B, LINK 04) and $J/\psi \to \omega\pi^+\pi^-$ (AUGUSTIN 89, ABLIKIM 04A). 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 background as required by chiral symmetry, and from crossed channel exchanges, the $f_0(1370)$, and other dynamical features; it may be generated by t-channel meson exchanges (LOHSE 90, ZOU 94). 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 $\bar{K}K$ 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.

One also observes the σ, and the $a_0(980)$, in radiative decays ($\phi \to f_0\gamma$, $\phi \to a_0\gamma$) in SND data (ACHASOV 00F, ACHASOV 00H), CMD2 (AKHMETSHIN 99B), and in KLOE data (ALOISIO 02C, ALOISIO 02D). In addition to these observations of the σ, its existence is also supported by the reaction $e^+e^- \to \pi^0\pi^0\gamma$ in the vicinity of the ρ and ω peaks. Both SND (ACHASOV 02F) and CMD-2 (AKHMETSHIN 04B) conclude that their value for the branching ratio $\rho \to \pi^0\pi^0\ \gamma$ exceeds the expectations from vector dominance, and that their results are much better described if a direct coupling of $\rho \to \sigma\ \gamma$ is added.

A meson resonance that is very well studied experimentally, is the $f_0(1500)$ seen by the Crystal Barrel experiment in five decay modes: $\pi\pi$, $\bar{K}K$, $\eta\eta$, $\eta\eta'(958)$, 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 (BARBERIS 99D, BARBERIS 00E) agree on the description of the S wave with the one above. The $\bar{p}p$, $\bar{n}p/\bar{p}n$ (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, ABELE01B). 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. 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. For example, GARMASH 02 saw a broad structure between 1.0 and 1.5 GeV in $\pi^+\pi^-, K^+K^-$ and $K\pi$ final states. 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: What is the nature of the light scalars? 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.

Almost every model on scalar states agrees that the $K^*(1430)$ is predominantly the quark model $s\bar{u}$ or $s\bar{d}$ 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) flavour nonet being the $(\bar{u}u + \bar{d}d)$, $u\bar{d}$

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. Assuming the three f_0's in the 1300-1700 MeV region to be mixtures between an $\bar{u}u$, $\bar{s}s$, 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-$\bar{q}q$ states.

The $f_0(980)$ and $a_0(980)$ are often interpreted as multi-quark states (JAFFE 77, ALFORD 00, MAIANI 04A) or $\bar{K}K$ 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. The $f_0(980)$ appears as a peak structure in $J/\psi \to \phi\pi^+\pi^-$ and in D_s decays without $f_0(600)$ background. Based on that observation it is suggested that $f_0(980)$ has a large $\bar{s}s$ component, which according to (DEANDREA 01) is surrounded by a virtual $\bar{K}K$ cloud. Data on radiative decays ($\phi \to f_0\gamma$ and $\phi \to a_0\gamma$) from SND, CMD2, and KLOE (see above) favour 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 flavours, the σ, $a_0(980)$, $f_0(980)$, and κ (or $K_0^*(1430)$) would form a nonet (not necessarily $\bar{q}q$), 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 the unitarized quark model with coupled $q\bar{q}$ and meson-meson channels, the light scalars can be understood as additional manifestations of bare $\bar{q}q$ 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 $f_0(1700)$), $K^*(1430)$, 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.

References

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