NON-$q\overline{q}$ MESONS

Written March 2000 by C. Amsler (University of Zürich)

See also $N\overline{N}(1100-3600)$ for possible multiquark states.

The constituent quark model describes the observed meson spectrum as bound $q\overline{q}$ states grouped into SU(3) flavor nonets. The self-coupling of gluons in QCD suggests that additional mesons made of bound gluons (glueballs) or $q\overline{q}$-pairs with an excited gluon (hybrids) may exist. Multiquark color singlet states like $qq\overline{q}\overline{q}$ or $qqq\overline{q}\overline{q}\overline{q}$ have also been predicted (JAFFE 77). Among the signatures naively expected for glueballs are (i) no place in $q\overline{q}$ nonets, (ii) enhanced production in gluon rich channels such as central production and radiative $J/\psi(1S)$ decay, (iii) decay branching fractions incompatible with SU(3) predictions for $q\overline{q}$ states, and (iv) reduced $\gamma\gamma$ couplings. However, mixing effects with isoscalar $q\overline{q}$ mesons (AMSLER 96, ANISOVICH 97, WEINGARTEN 97,CLOSE 97B) and decay form factors (BARNES 97) may obscure these simple signatures.

Lattice calculations (BALI 93, SEXTON 95, MORNINGSTAR 99), QCD sum rules, flux tube and constituent glue models agree that the lightest glueballs have quantum numbers $J^{PC}=0^{++}$ and 2^{++} (for a review see SWANSON 97). On the lattice, the scale parameter (estimated from the string tension in heavy quark mesons) gives by extrapolation to zero lattice spacing a mass of 1611 $\pm$ 163 MeV for the ground state (0^{++}) glueball, while the first excited state (2^{++}) has a mass of 2232 $\pm$ 310 MeV (MICHAEL 97). Hence the low mass glueballs lie in the same mass region as ordinary isoscalar $q\overline{q}$ states, that is in the mass range of the $1^3P_0(0^{++})$, $2^3P_2, 3^3P_2$, and $1^3F_2(2^{++})$ $q\overline{q}$ states. The 0^{-+} state and exotic glueballs (with non-$q\overline{q}$ quantum numbers like 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, *etc.*) are expected above 2 GeV (BALI 93).

The lattice calculations assume that the quark masses are infinite and therefore neglect $q\overline{q}$ loops. However, one expects that glueballs will mix with nearby $q\overline{q}$ states of the same quantum numbers. The effect of $q\overline{q}$ loops on the glueball mass is not clear and the size of the $q\overline{q}$ admixture in the glueball wavefunction is not predicted by lattice calculations. However, the presence of a glueball mixed with $q\overline{q}$ would still lead to a supernumerary isoscalar in the SU(3) classification of $q\overline{q}$ mesons.

For earlier experimental searches we refer to the Notes in the 1996 and 1998 issues of this Review. See also the review on exotic mesons by LANDSBERG 99.

We first deal with non-$q\overline{q}$ candidates in the scalar sector. Five isoscalar resonances are well established: the very broad $f_0(400-1200)$ (or σ), the $f_0(980)$, the broad $f_0(1370)$, and the comparatively narrow $f_0(1500)$ and $f_0(1710)$ (see the Note on "Scalar Mesons" and also AMSLER 98). The $f_0(1500)$ was observed in many experiments, *e.g.*, in pion induced reactions π^-p (BINON 83, AMELIN 96B), in $\overline{p}p$ annihilations (AMSLER 95B, 95C, BERTIN 97C), in central collisions (REYES 98, BARBERIS 99, BELLAZZINI 99), in J/ψ radiative decays (BUGG 95) and in D_s decays (FRABETTI 97D). The $f_0(1710)$, with controversial spin (0 or 2), was recently shown to have spin 0 (DUNWOODIE 97, BARBERIS 99, FRENCH 99) and to decay mainly into $K\overline{K}$ (BARBERIS 99, 99B, 99D). This points to a mostly $s\overline{s}$ structure, although no signal was reported in $K^-p\to K_SK_S\Lambda$ interactions, but the data sample was rather small (ASTON 88D). In $\gamma\gamma$ collisions leading to K_SK_S (BRACCINI 99) a signal is observed at the $f_0(1710)$ mass (although its spin cannot be determined) but $f_0(1500)$ is absent, while in $\gamma\gamma$ collisions leading to $\pi^+\pi^-$ neither $f_0(1710)$ nor $f_0(1500)$ are observed (BARATE 00E). The production rate for $f_0(1710)$ and the absence of $f_0(1500)$ in both $K\overline{K}$ and $\pi\pi$ favor the former to be mainly $s\overline{s}$ and the latter to have a small coupling to $\gamma\gamma$ at most compatible with an $s\overline{s}$ state (AMSLER 99).

On the other hand, the $K\overline{K}$ decay branching ratio of $f_0(1500)$ is small compared to $\pi\pi$ (ABELE 96B, 98, BARBERIS 99D) indicating that this state cannot be dominantly $s\overline{s}$. Since $f_0(1370)$ does not couple strongly to $s\overline{s}$ either (BARBERIS 99D), $f_0(1370)$ or $f_0(1500)$ appear to be supernumerary. Note that $f_0(1370)$ and $f_0(1500)$ have rather different decay patterns. The former decays to $\sigma\sigma$ and $\rho\rho$, while the latter does not decay to $\rho\rho$ (BUGG 95, THOMA 99). The narrow width of $f_0(1500)$ and its enhanced production at low transverse momentum transfer in central collisions (CLOSE 97, 98B) favor $f_0(1500)$ to be non-$q\overline{q}$. In AMSLER 96 the ground state scalar nonet is made of $a_0(1450)$, $f_0(1370)$, $K_0^*(1430)$ and the at the time missing $s\overline{s}$ state which could now be identified as $f_0(1710)$. The isoscalars $f_0(1370)$ and $f_0(1710)$ contain a small fraction of glue while $f_0(1500)$ is mostly gluonic. Alternative, less straightforward, mixing schemes have been proposed (TORNQVIST 96, ANISOVICH 97, BOGLIONE 97, WEINGARTEN 97, MINKOWSKI 99).

The $a_0(980)$ and $f_0(980)$ could be four-quark states (JAFFE 77) or $K\overline{K}$ molecular states (WEINSTEIN 90, LOCHER 98) due to their strong affinity for $K\overline{K}$, in spite of their masses being very close to threshold. For $q\overline{q}$ states the expected $\gamma\gamma$ widths (OLLER 97B, DELBOURGO 99) are not significantly larger than for molecular states (BARNES 85). A better filter might be radiative $\phi(1020)$ decay to $a_0(980)$ and $f_0(980)$. Recent data (ACHASOV 98B, 98I, AKHMETSHIN 99C) favor these mesons to be four-quark states (ACHASOV 97C), although not everybody agrees (MALTMAN 99B, DELBOURGO 99). Also, the $f_0(980)$ is strongly produced in D_s^+ decay (FRABETTI 97), suggesting a large $s\overline{s}$ component, while hadronic Z^0 decay favors in contrast a large $u\overline{u}+d\overline{d}$ component (ACKERSTAFF 98Q).

We now turn to the 2^{++} sector. The isoscalar $1^3P_2(2^{++})$ $q\overline{q}$ mesons, $f_2(1270)$, and $f_2'(1525)$, are well known. Above the $f_2'(1525)$ none of the reported isoscalars can be definitely assigned to the 2^3P_2, 3^3P_2, or 1^3F_2 nonets and therefore the identification of the 2^{++} glueball is premature. Three states appear to be solid. The $f_2(1565)$ observed in $\overline{p}p$ annihilation at rest (MAY 90, BERTIN 98) is perhaps the same state as $f_2(1640)$ reported to decay into $\omega\omega$ (ALDE 90, BAKER 99) and 4π (ADAMO 92). This could be one of the 2^3P_2 isoscalars or a nucleon-antinucleon resonance. The rather broad

$f_2(1950)$ is observed by several experiments, *e.g.*, in central production (BARBERIS 97B) and in $\overline{p}p$ annihilation in flight (ABELE 99B). Finally, a broad structure (of perhaps several states) decaying to $\phi\phi$ was reported around 2300 MeV in $\pi^- N$ reactions (BOOTH 86, ETKIN 88) in $\overline{p}p$ annihilation in flight (EVANGELISTA 98) and in central collisions (BARBERIS 98).

The evidence for a narrow meson, $f_J(2220)$ (possibly a tensor), is fading with new formation data in $\overline{p}p$ annihilation (KISIEL 99, see the Note under the $f_J(2220)$ section). The measured partial width to $\overline{p}p$ in radiative J/ψ decay (BAI 96B) is too large and inconsistent with the upper limit from $\overline{p}p$ annihilation into $\pi\pi$ (AMSLER 99). However, the suprisingly large $\phi\phi$ cross section in $\overline{p}p$ just above threshold (EVANGELISTA 98) could be due to the production of the 2^{++} glueball. In fact, the broad enhancement was reanalyzed by PALANO 99. The dominating contribution was found to be 2^{++}, resonating at a mass of 2231 MeV with a width of 70 MeV, in accord with earlier observations in $\pi^- N$ reactions (BOOTH 86, ETKIN 88).

Let us now deal with hybrid states. Hybrids may be viewed as $q\overline{q}$ mesons with a vibrating gluon flux tube. In contrast to glueballs, they can have isospin 0 and 1. The mass spectrum of hybrids with exotic (non-$q\overline{q}$) quantum numbers was predicted by ISGUR 85 while CLOSE 95 also deals with non-exotic quantum numbers. The ground state hybrids with quantum numbers (0^{-+}, 1^{-+}, 1^{--}, and 2^{-+}) are expected around 1.7 to 1.9 GeV. Lattice calculations predict that the hybrid with exotic quantum numbers 1^{-+} lies at a mass of 1.9 ± 0.2 GeV (LACOCK 97, BERNARD 97). Most hybrids are rather broad but some can be as narrow as 100 MeV (PAGE 99). They prefer to decay into a pair of S- and P-wave mesons.

A $J^{PC} = 1^{-+}$ exotic meson with a mass of 1370 MeV and a width of 385 MeV was reported in $\pi^- p \rightarrow \eta\pi^- p$ (THOMPSON 97, CHUNG 99). This state, called $\hat{\rho}(1405)$ in our previous edition, has now been renamed $\pi_1(1400)$. It was observed as an interference between the angular momentum $L = 1$ and $L = 2$ $\eta\pi$ amplitudes, leading to a forward/backward asymmetry in the $\eta\pi$ angular distribution. This state was reported earlier in $\pi^- p$ reactions (ALDE 88B) but ambiguous solutions in the partial wave analysis were pointed out by PROKOSHKIN 95B, 95C. A resonating 1^{-+} contribution to the $\eta\pi$ P-wave is also required in the Dalitz plot analysis of $\overline{p}n$ annihilation into $\pi^-\pi^0\eta$ (ABELE 98B) and in $\overline{p}p$ annihilation into $\pi^0\pi^0\eta$ (ABELE 99). The mass of 1400 MeV and the width of 310 MeV (ABELE 98B) are consistent with THOMPSON 97.

Another 1^{-+} state at 1593 MeV with a width of 168 MeV, $\pi_1(1600)$, decaying into $\rho\pi$ was reported in the reaction $\pi^- p \rightarrow \pi^-\rho^0 n$ (ADAMS 98B). It was observed earlier in the decay modes $\rho\pi$, $\eta'\pi$, and $b_1(1235)\pi$, but not $\eta\pi$ (GOUZ 92). A strong enhancement in the 1^{-+} $\eta'\pi$ wave, compared to $\eta\pi$, was reported at this mass by BELADIDZE 93. DONNACHIE 98 suggest that a Deck generated $\eta\pi$ background from final state rescattering in $\pi_1(1600)$ decay could mimick $\pi_1(1400)$. However, this mechanism is absent in $\overline{p}p$ annihilation. The $\eta\pi\pi$ data require $\pi_1(1400)$ and cannot accommodate a state at 1600 MeV (DUENNWEBER 99).

Hence we now have evidence for two 1^{-+} exotics, $\pi_1(1400)$ and $\pi_1(1600)$, while the flux tube model and the lattice concur to predict a mass of about 1.9 GeV, where a signal had been reported earlier (LEE 94). As isovectors, $\pi_1(1400)$ and $\pi_1(1600)$ cannot be glueballs. The coupling to $\eta\pi$ of the former points to a four-quark state while the strong $\eta'\pi$ coupling of the latter is favored for hybrid states (CLOSE 87B). Its mass is not far below the lattice prediction.

Finally, 0^{-+}, 1^{--}, and 2^{-+} hybrids were also reported. The $\pi(1800)$ decays mostly to a pair of S- and P-wave mesons (AMELIN 95B), in line with expectations for a 0^{-+} hybrid meson, although recent data contradict this, indicating a strong $\rho\omega$ decay mode (ZAITSEV 97). This meson is also rather narrow if interpreted as the second radial excitation of the the pion. The evidence for 1^{--} hybrids required in e^+e^- annihilation and in τ decays has been discussed by DONNACHIE 99. A candidate for the 2^{-+} hybrid, the $\eta_2(1870)$, was reported in $\gamma\gamma$ interactions (KARCH 92), in $\overline{p}p$ annihilation (ADOMEIT 96) and in central production (BARBERIS 97B). The near degeneracy of $\eta_2(1645)$ and $\pi_2(1670)$ suggests ideal mixing in the 2^{-+} $q\overline{q}$ nonet and hence the second isoscalar should be mainly $s\overline{s}$. However, $\eta_2(1870)$ decays mainly to $a_2(1320)\pi$ and $f_2(1270)\pi$ (ADOMEIT 96) with a relative rate compatible with a hybrid state (CLOSE 95).