NON-$q\overline{q}$ MESONS

The existence of gluon self coupling in QCD suggests that gluonia (or glueballs) and hybrids ($q\overline{q}g$) might exist. Another possible kind of non-$q\overline{q}$ mesons is multiquark states. For detailed reviews, see HEUSCH 86, CLOSE 87, TOKI 88, and BURNETT 90. Among the signatures naively expected for glueballs are (i) no place in $q\overline{q}$ nonets, (ii) flavor-singlet couplings, (iii) enhanced production in gluon-rich channels such as $J/\psi(1S)$ decay, and (iv) reduced $\gamma\gamma$ coupling. However, mixing effects with $q\overline{q}$ states, and other dynamical effects such as form factors, may obscure these simple signatures. If mixing is large, only the finding of more states than are predicted by the $q\overline{q}$ quark model remains as a clear signal for non-exotic non-$q\overline{q}$ states.

Lattice gauge theory calculations in the quenched approximation (without quark loops) predict the lightest glueball to be a scalar with a mass of typically 1550±95 MeV (BALI 93). The same calculations find a tensor glueball mass of 2270±100 MeV, and glueballs with other spin-parities are predicted to be still heavier. A more recent lattice calculation (SEXTON 95) predicts a slightly higher mass, 1740 ± 71 MeV. Including dynamical quarks will, however, change the predicted masses.

Hybrid mesons are $q\overline{q}$ states combined with a gluonic excitation (BARNES 82, CHANOWITZ 83, ISGUR 85, CLOSE 95). Hybrids span flavor nonets, may have exotic (non-$q\overline{q}$) quantum numbers (a $J^{PC} = 1^{-+}$ state is expected in all models), and are predicted to have characteristic decay modes (LEYAOUANC 85, CLOSE 95). The masses of the lightest hybrids are typically predicted to be in the range 1500 to 2000 MeV. Charm hybrids ($c\overline{c}g$) are attractive experimentally since they may appear as supernumerary states in the predictable charmonium spectrum. The $\psi(4040)$ and $\psi(4160)$ are possibly mixtures of $c\overline{c}$ and $c\overline{c}g$ states (CLOSE 96).

The third class of non-$q\overline{q}$ states, the multiquark states, can be either baglike or clusters of mesons (VOLOSHIN 76, JAFFE 77, GUTBROD 79). A subclass of the latter are the deuteronlike meson-meson bound states, or deusons, where the long-range pion exchange is the major source of binding (TORNQVIST 91 and 94, ERICSON 93, MANOHAR 93). Many of the best non-$q\overline{q}$ candidates discussed below lie close to important thresholds, which suggests that they might be bound states of a meson pair. Examples include the $f_0(980)$ and $a_0(980)$ (close to the $K\overline{K}$ threshold), the $f_1(1420)$ (above the $K\overline{K}^*$ threshold, thus not a bound state but perhaps a threshold enhancement), the $f_0(1500)$ and $f_2(1520)$ ($\omega\omega$ and $\rho\rho$), the $f_J(1710)$ ($K^*\overline{K}^*$), and the $\psi(4040)$ ($D^*\overline{D}^*$). Many suggestions for such mesonium candidates, involving both light and heavy quarks and binding mechanisms, have appeared (WEINSTEIN 90, DOVER 91, BARNES 92, DOOLEY 92).

The candidates we discuss below are chosen because they are difficult to interpret as conventional $q\overline{q}$ states. We do not see it as our task to discuss theoretical interpretations of the candidates, but merely to catalogue the observations of possible relevance.

Scalar mesons: There are four known isoscalars with $J^{PC} = 0^{++}$: the $f_0(400\text{–}1200)$, a very broad structure around 800 MeV, the $f_0(980)$, the $f_0(1370)$, and the $f_0(1500)$; the spin of another established isoscalar, the $f_J(1710)$, may be 0 or 2. In the quark model, one expects two 1^3P_0 states and one 2^3P_0 $(u\overline{u}+d\overline{d})$-like state below 1.8 GeV. Thus, there are too many scalars to find a place in the quark model.

However, for scalar resonances, naive quark model expectations, in particular ideal mixing, could be strongly broken by the opening of inelastic thresholds. Thus, the physical scalar $q\overline{q}$ spectrum may be very much distorted from naive expectations. For a detailed discussion of this sector, see our Note under the $f_0(1370)$.

In this edition, we have merged the $f_0(1590)$ observed in $\pi^- p$ interactions at high energies with the $f_0(1525)$ observed in $\overline{p}p$ annihilations, under the new name $f_0(1500)$. The $\pi\pi$ and $\eta\eta$ S-waves have a T-matrix pole at $m - i\Gamma/2 \sim 1500 - i60$ MeV, which corresponds to the physical mass and width (AMSLER 95B, AMSLER 95C), while a simple Breit-Wigner description gives a slightly higher mass and width (AMSLER 92, ALDE 88). For consistency, we average the mass and width determined by the T-matrix poles. A coupled-channel analysis taking unitarity constraints into account has been performed in $\overline{p}p$ (AMSLER 95D) but not in $\pi^- p$. Thus, we do not view the apparent discrepancies in the decay branching ratios to $\pi^0\pi^0$, $\eta\eta$, and $\eta\eta'$ between the $\overline{p}p$ and $\pi^- p$ experiments to be serious.

In the model of AMSLER 95E and AMSLER 96, the (nearly ideally mixed) ground state scalar $q\overline{q}$ nonet consists of the $a_0(1450)$, the $K_0^*(1430)$, the $f_0(1370)$, and the still missing isoscalar $s\overline{s}$ state, which cannot be the $f_0(1500)$ due to its comparatively narrow width and low $K\overline{K}$ decay branching ratio. The $f_0(1500)$ is interpreted as a scalar glueball mixed with the two nearby $q\overline{q}$ isoscalars.

The $f_J(1710)$ (whose spin is uncertain) has been seen mainly in the gluon-rich $J/\psi(1S)$ radiative decay, where it is copiously produced. Before 1991, the spin of the $f_J(1710)$ was believed to be 2, and the subsequent spin-0 determination in $J/\psi(1S)$ radiative decay (CHEN 91) has not been confirmed. In central production, the WA76 experiment (ARMSTRONG 89D) on 300 GeV/c pp interactions sees a structure at the same mass, but favors spin 2. The $f_J(1710)$ has not been seen in hadronic production ($K^- p \rightarrow K\overline{K}\Lambda$) (ASTON 88D), nor in $\gamma\gamma$ fusion. The ratio of the branching fractions in $J/\psi(1S) \rightarrow \omega f_J$ and $J/\psi(1S) \rightarrow \phi f_J$ suggests that nonstrange and strange components are both important in this state. Its mass and width are consistent with the prediction for the ground-state glueball, according to the most recent lattice gauge calculations (SEXTON 95), if one assumes that the spin is indeed zero.

Pseudoscalar mesons: The established isoscalars with $J^{PC} = 0^{-+}$ are the η, the $\eta'(958)$, the $\eta(1295)$, and the $\eta(1440)$ [which may be two pseudoscalar resonances, an $\eta(1410)$ and an $\eta(1490)$; see the Note under the $\eta(1440)$]. In the $q\overline{q}$ model, one expects two 1^1S_0 and two 2^1S_0 pseudoscalars between 500 and 1800 MeV.

Identifying the $\eta(1280)$ with the 2^1S_0 $(u\overline{u} + d\bar{d})$ state is natural, but it is more problematic to identify one of the two peaks in the $\eta(1440)$ region with the 2^1S_0 $s\bar{s}$ state. The $\eta(1440)$ is observed in $s\bar{s}$-depleted reactions like $\pi^- p \rightarrow \eta\pi\pi n$ (ANDO 86), $p\overline{p}$ annihilation (BAILLON 67, AMSLER 95F, BERTIN 95), and $\pi^- p \rightarrow a_0(980)\pi p$ (CHUNG 85, BIRMAN 88), and is not seen in the $s\bar{s}$-enriched channels like $K^-p \to K^*(892)\overline{K}\Lambda$ (ASTON 87). The fact that ANDO 86 sees the $\eta(1440)$ and $\eta(1280)$ with similar intensities argues that these states are of a similar nature, *e.g.*, radial excitations of the η and $\eta'(958)$. However, as there are suggestions that the $\eta(1440)$ is in fact two η's, the situation remains confused.

The $\pi(1770)$ (BERDNIKOV 94, AMELIN 95B) has a surprisingly narrow width (if interpreted as the second radial excitation of the π), a large coupling to $K\overline{K}$, and decays to a pair of mesons, one with $\ell(q\overline{q}) = 0$, the other with $\ell(q\overline{q}) = 1$. This is the signature expected for a hybrid meson (CLOSE 95).

Axial-vector mesons: The $q\overline{q}$ model predicts a nonet that includes two isoscalar 1^3P_1 states with masses below about 1.6 GeV. Three such 1^{++} states are known, the $f_1(1285)$, the $f_1(1420)$, and the $f_1(1530)$, which suggests that one of these is a non-$q\overline{q}$ meson. The $f_1(1420)$ is the most likely candidate: see CALDWELL 90 and the Note under the $f_1(1420)$. The proximity of the $K\overline{K}^*$ threshold suggests this may be a dominantly $K\overline{K}^*$ mesonium resonance or a threshold enhancement (LONGACRE 90, TORNQVIST 91).

Tensor mesons: The two 1^3P_2 $q\overline{q}$ states are very likely the well-known $f_2(1270)$ and $f_2'(1525)$. There are several other states, which have been suggested as $J^{PC} = 2^{++}$ non-$q\overline{q}$ candidates: the $f_2(1430)$, $f_2(1520)$, $f_J(1710)$, $f_2(1810)$, $f_2(2010)$, $f_2(2150)$, $f_2(2300)$, and $f_2(2340)$.

The $f_2(1520)$ is observed by the ASTERIX Collaboration (MAY 89) in $p\overline{p}$ P-wave annihilation in the $\pi^+\pi^-\pi^0$ channel and by the Crystal Barrel Collaboration (ANISOVICH 94, AMSLER 95B) in $3\pi^0$, close to the $\rho\rho$ and $\omega\omega$ thresholds. It has no place in a $q\overline{q}$ scheme, since all nearby $q\overline{q}$ states are already accounted for. Similarly, the $f_J(1710)$ could be composed of $K^*\overline{K}^*$ and $\omega\phi$ (DOOLEY 92), since it lies close to these thresholds.

Of the heavier states, the $f_2(1810)$ is likely to be the 2^3P_2, and among those above 2 GeV one expects the 2^3P_2 $s\bar{s}$, 1^3F_2 $s\bar{s}$, and 3^2P_2 $s\bar{s}$, but a gluonium interpretation of one of the four states is not excluded. These three f_2 resonances have been observed in the OZI-rule forbidden process $\pi p \to \phi\phi n$ (ETKIN 88), which has been claimed as favoring the gluonium interpretation.

A similar $\phi\phi$ mass spectrum is seen by ARMSTRONG 89B in the Ω spectrometer. The DM2 and MARK-III collaborations see threshold $\phi\phi$ production, but favor $J^P = 0^-$, not 2^+.

In $\gamma\gamma \to 4\pi$ near the $\rho\rho$ threshold, TASSO (BRANDELIK 80B, ALTHOFF 82), MARK2 (BURKE 81), CELLO (BEHREND 84E), PLUTO (BERGER 88B), SLAC TPC (AIHARA 88), and ARGUS (ALBRECHT 91F) observe a resonance-like structure. This is dominated by $\rho^0\rho^0$, and the cross section peaks a little above the $f_2(1520)$. This process has not been explained by models in which only conventional resonances dominate. The fact that the $\gamma\gamma \to \rho^+\rho^-$ is small (ALBRECHT 91F quotes 1/4 for the $\rho^+\rho^-/\rho^0\rho^0$ ratio) requires both isospin 0 and 2 for the $\rho\rho$ system. A resonance interpretation in terms of $q^2\overline{q}^2$ states thus requires the presence of a flavor exotic $I = 2$ resonance (ACHASOV 82, 87, 90). The 2^{++} partial wave is found to dominate the $\rho\rho$ structure (BERGER 88B, ALBRECHT 91F), with some 0^{++} at the low- energy end, while $J^P = 0^-$ and 2^- contribute very little.

In $\gamma\gamma \to \omega\rho$ and $\phi\rho$, there are also broad enhancements that peak near 1.7 GeV. The dominant partial wave is 2^{++} in $\omega\rho$, while 2^{-+} is favored in $\phi\rho$ (ALBRECHT 94Z).

Other exotic or non-$q\overline{q}$ candidates: An isovector $\phi\pi^0$ resonance at 1480 MeV has been reported by BITYUKOV 87 in $\pi^- p \to \phi\pi^0 n$ (listed under the $\rho(1450)$). Preliminary indications favor the nonexotic $J^{PC} = 1^{--}$, but the large OZI-rule violating branching ratio $\phi\pi$:$\omega\pi$ seems peculiar for a ($u\overline{u}$-$d\overline{d}$) $I=1$ $q\overline{q}$ object. However, ACHASOV 88 shows that the threshold effect from the two-step process $\rho(1600) \to K\overline{K}^* \to \pi\phi$ can violate the rule, especially near threshold. No sign of this candidate is seen in $\pi\omega$ (FUKUI 91). In addition, the small coupling to the photon makes an identification with the $\rho(1450)$ difficult (CLEGG 88). More recently DONNACHIE 93, analyzing e^+e^--annihilation and diffractive-photoproduction data, suggests there may be 4-quark states near 1100 and 1300 MeV.

Another exotic candidate is the $\hat{\rho}(1405)$ (ALDE 88B, IDDIR 88), seen in the GAMS experiment under the $a_2(1320)$ in $\pi^- p \rightarrow \eta\pi^0 n$ with the exotic quantum numbers $J^{PC} = 1^{-+}$. The analysis of ALDE 88B has, however, been questioned by PROKOSHKIN 95B, 95C. Although the forward-backward asymmetry demands an $\eta\pi$ P-wave, it may be due to a nonresonant amplitude. The Crystal Barrel Collaboration has reported results on the corresponding P-wave in $\eta\pi$ seen in $p\overline{p} \rightarrow \eta\pi\pi$; they see a much broader effect, which can be explained as nonresonant or as a resonance with $\Gamma \approx 600$ MeV (AMSLER 94D). AOYAGI 93 also notes the $\eta\pi$ P-wave, but its interpretation is unclear.

Another possible 1^{-+} candidate is the isosinglet $X(1910)$ (ALDE 89), which seems to decay to $\eta\eta'$ but not to $\pi^0\pi^0$ or $\eta\eta$ (ALDE 89). An enhancement with quantum numbers 1^{-+}, decaying to $f_1(1285)$, has also been reported around 1900 MeV (LEE 94).

A narrow resonance, listed under the $K_J(3100)$, has been reported at about 3100 MeV (BOURQUIN 86, ALEEV 93) in several $\Lambda\overline{p}+$pions and $\overline{\Lambda}p+$pions states. The observation of the doubly-charged states $\Lambda\overline{p}\pi^-$ and $\overline{\Lambda}p\pi^+$ implies, assuming the decay is strong, $I = 3/2$, clearly not a $q\overline{q}$ state. In addition, a narrow peak is observed at about 3250 MeV, listed under the $X(3250)$, in the hidden strangeness combinations containing a baryon-antibaryon pair (ALEEV 93). However, all these observations need confirmation.