NON-$q\overline{q}$ MESONS

The existence of a gluon self coupling in QCD suggests that, in addition to conventional $q\overline{q}$ meson states, there may exist bound states including gluons: gluonia or glueballs, and hybrids ($q\overline{q}g$). Another example of non-$q\overline{q}$ mesons is multiquark states. For detailed reviews, see, *e.g.*, HEUSCH 86, CLOSE 87, TOKI 88, GODFREY 89, BURNETT 90. Theoretical guidance for the properties of these states is somewhat contradictory, and models often differ in detailed predictions.

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;
(iv) Reduced $\gamma\gamma$ coupling;
(v) Exotic quantum numbers not allowed for $q\overline{q}$ (in some cases).

However, mixing effects, and other dynamical effects such as form factors, may obscure these simple signatures. If the mixing is large, only overpopulation of the spectrum relative to the number of states predicted by the $q\overline{q}$ quark model remains as a clear signal for non-exotic non-$q\overline{q}$ states. Exotic quantum numbers ($J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \cdots$) would be the best signature for 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±50 MeV (BALI 93). The same calculation finds a tensor glueball mass of 2270±100 MeV, and glueballs with other spin parities, which include the J^{PC}-exotics, are predicted to be still heavier. The inclusion of dynamical quarks will change the predicted masses through couplings to decay channels. Very little is known about the expected widths, which may conceivably be very large.

Hybrid mesons are $q\overline{q}$ states combined with a gluonic excitation (BARNES 82, CHANOWITZ 83, ISGUR 85). Experimentally, these are more attractive than glueballs because they span flavor nonets, and are predicted to have characteristic decay modes (LEYAOUANC 85), and a $J^{PC} = 1^{-+}$ exotic

hybrid is expected in all models. The masses of the lightest hybrids are typically predicted to be in the range 1500–2000 MeV.

The third class of non-$q\overline{q}$ states are the multiquark states, which 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 an important threshold, which suggests that they may 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 $K\overline{K}^*$, thus not a bound state but perhaps a threshold enhancement), the $f_0(1525)$ 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 recently (WEINSTEIN 90, DOVER 91, BARNES 92, DOOLEY 92).

It should be emphasized that no state has been identified unambiguously as a glueball, hybrid, or multiquark state. The candidates we discuss below are chosen because they are difficult to interpret as conventional $q\overline{q}$ states. Note, however, that we do not see it as our task to discuss theoretical interpretations of the candidates; rather, we merely catalogue the observations of possible relevance.

The scalar-meson sector: The established isoscalars with $J^{PC} = 0^{++}$ are the $f_0(980)$, $f_0(1300)$, $f_0(1370)$, and $f_0(1590)$; the $f_J(1710)$ is an established isoscalar whose spin may be 0. 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 well-established scalars to find a place in the quark model. From further dynamical arguments related to the production or decay, it is very likely that both the $f_0(1590)$ and the $f_J(1710)$ are non-$q\overline{q}$ resonances.

It should, however, be noted that for scalar resonances with strong S-wave thresholds, naive quark model expectations, in particular ideal mixing, must be strongly broken by unitarity.

Thus, the physical scalar $q\overline{q}$ spectrum can be very much distorted from naive expectations. Another problem is that mass determinations of a very broad resonance like the $f_0(1300)$ or the $K_0^*(1430)$ are always somewhat dependent on the model and background assumptions. For a detailed discussion of this sector, see our note on "S-wave $\pi\pi$, $K\overline{K}$, and $\eta\eta$ Interactions."

The $f_0(1590)$, seen in $\pi^- p$ reactions at 38 GeV/c (BINON 83, BINON 84C, ALDE 87, ALDE 87B), has a peculiar decay pattern for a $q\overline{q}$ state:

$$\pi^0\pi^0 : K\overline{K} : \eta\eta : \eta\eta\prime : 4\pi^0 =< 0.3 : < 0.6 : 1 : 2.7 : 0.8$$

The scalar glueball and the $^3P_0$ $s\overline{s}$ state are both expected near this mass, so we may here be seeing the effects of more than one resonance.

The $f_J(1710)$ (whose spin is uncertain) has been seen mainly in "gluon-rich" $J/\psi(1S)$ radiative decay, where it is copiously produced. In central production, the WA76 experiment (ARMSTRONG 89D) on 300 GeV/c pp interactions n sees a structure at the same mass, but favors spin 2. The $f_J(1710)$ has not been seen in hadronic production ($K^- p \to K\overline{K}\Lambda$) (ASTON 88D), nor in $\gamma\gamma$ fusion. The ratio of the branching fractions in $J/\psi \to \omega f_J$ and $J/\psi \to \phi f_J$ suggests important nonstrange and strange components in this state.

The pseudoscalar sector: The established isoscalars with $J^{PC} = 0^{-+}$ are the η, $\eta\prime(958)$, $\eta(1280)$, and $\eta(1440)$ [which may be two pseudoscalar resonances $\eta(1410)$ and $\eta(1490)$; see the note on the "$\eta(1440)$"]. In the $q\overline{q}$ model, we expect two 1^1S_0 and two 2^1S_0 pseudoscalars in the 500–1800 MeV range.

Identifying the $\eta(1280)$ with the 2^1S_0 $(u\overline{u} + d\overline{d})$ state seems natural, but it is more problematic to assign one of the two peaks in the $\eta(1440)$ region to the 2^1S_0 $s\overline{s}$ state. The $\eta(1440)$ is observed in $s\overline{s}$-depleted reactions like $\pi^- p \to \eta\pi\pi n$ (ANDO 86) and $\pi^- p \to a_0(980)\pi p$ (CHUNG 85, BIRMAN 88), and is not seen in the $s\overline{s}$-enriched channels like $K^- p \to K^*(892)\overline{K}\Lambda$ (ASTON 87). The fact that ANDO 86 sees the $\eta(1440)$ bump and the $\eta(1280)$ with similar intensities argues for these states being of a similar nature, *i.e.*, radial excitations of the η and

$\eta'(958)$. However, as there are suggestions of two resonances in the $\eta(1440)$ structure, the experimental situation remains confused and the nature of the $\eta(1440)$ is not well understood.

The axial-vector meson sector: 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 $f_1(1285)$, $f_1(1420)$, and $f_1(1530)$, which suggests that one of these is a non-$q\overline{q}$ meson. The $f_1(1420)$ is the most likely candadate; see CALDWELL 89 and the note on the "$f_1(1420)$." The proximity of the $K\overline{K}^*$ threshold suggests this may be a dominantly $K\overline{K}^*$ mesonium resonance or threshold enhancement (LONGACRE 90, TORNQVIST 91).

The tensor meson sector: 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 $f_2(1430)$, $f_2(1520)$, $f_J(1710)$, $f_2(1810)$, $f_2(2010)$, $f_2(2300)$, and $f_2(2340)$.

The $f_2(1520)$ is observed by the ASTERIX collaboration (MAY 89) in $p\overline{p}$ P-wave annihilation at 1565 MeV in the $\pi^+\pi^-\pi^0$ channel. Its mass is better determined in the $3\pi^0$ mode by the Crystal Barrel (ANISOVITCH 94) to be 1520 MeV, 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 occupied.

Similarly, the $f_J(1710)$ could be composed of $K^*\overline{K}^*$ and $\omega\phi$ (DOOLEY 92), since it lies close to these thresholds. Note that before 1991, the spin of the $f_J(1710)$ was believed to be 2, and that the subsequent spin-0 determination (CHEN 91) has not been confirmed. As already mentioned, in central production WA76 still favours spin 2 for their 1720-MeV structure.

Of the heavier states, the $f_2(1810)$ is likely to be the 2^3P_2 and the three f_2's above 2 GeV could possibly be the 2^3P_2 $s\overline{s}$, 1^3F_2 $s\overline{s}$, and 3^3P_2 $s\overline{s}$, but a gluonium interpretation of one of the three 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 cited 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). For this $\rho\rho$ structure, the 2^{++} partial wave is found to be dominant (BERGER 88B, ALBRECHT 91F), with some 0^{++} at the low-energy end, while $J^P = 0^-$ and 2^- contribute very little.

In $\gamma\gamma \to \omega\rho$, there is also a broad enhancement that peaks near 1.6 GeV (BEHREND 91, WEGNER 91), which is probably composed of several spin parities (BEHREND 91).

Other exotic or non-$q\overline{q}$ candidates: An isovector $\phi\pi^0$ resonance at 1480 MeV has been reported by BITYUKOV 87 in $\pi^-p \to \phi\pi^0 n$; see the $\rho(1450)$. Preliminary indications favor $J^{PC} = 1^{--}$, *i.e.* nonexotic, 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 $\pi^-p \to \eta\pi^0 n$ with the exotic quantum numbers $J^{PC} = 1^{-+}$.

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 $p\overline{p} \to \eta\pi\pi$; they see a much broader effect, which can be explained as nonresonant or as a resonance with $\Gamma \approx 600$ MeV. AOYAGI 93 also notes the $\eta\pi$ P-wave, but its interpretation is unclear.

For another possible 1^{-+} candidate, see the isosinglet $X(1910)$.

A narrow resonance, listed under $K_J^?(3100)$, 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 $X(3250)$, in the "hidden strangeness" combinations containing a baryon-antibaryon pair (ALEEV 93). However, all these observations need confirmation.