NON-$q\overline{q}$ MESONS

Written March 1998 by R. Landua (CERN).

The constituent quark model describes the observed meson spectrum as bound $q\overline{q}$ states grouped into SU(3) flavour nonets. The existence of gluon self-coupling in QCD suggests that additional bound states of gluons (glueballs gg, ggg) or hybrids ($q\overline{q}g$) might exist. Another possible kind of non-$q\overline{q}$ mesons is multiquark states ($qq\overline{q}\overline{q}$, or $q\overline{q}$-$q\overline{q}$).

A glueball has no place in a $q\overline{q}$ nonet, it is a flavour-singlet, produced mainly in gluon-rich channels (radiative $J/\psi(1S)$ decays, antiproton-proton annihilation), and has a small gamma-gamma coupling. However, mixing with $q\overline{q}$ mesons of the same quantum numbers will modify the expected glueball signatures, such as flavour-blind decay modes. If the mixing is large, only the finding of more states than predicted by the quark model remains a clear signal for a non-$q\overline{q}$ state. Theoretical calculations based on lattice gauge theory and QCD sum rules agree that the lightest glueball should be a scalar resonance ($J^{PC} = 0^{++}$) with a mass of 1600 ± 150 MeV (BALI 93, SEXTON 95), followed by a tensor (2^{++}) and a pseudoscalar (0^{-+}) glueball in the 2000–2500 MeV mass region (SZCZEPANIAK 96).

Hybrid mesons are $q\overline{q}$ states combined with a gluonic excitation, allowing exotic (non-$q\overline{q}$) quantum numbers such as $J^{PC} = 1^{-+}$). Hybrids span flavour nonets. In flux tube models, they are predicted to have characteristic decay modes into a pair of $S^-(l = 0)$ and $P^-(l = 1)$ wave mesons (ISGUR 85, CLOSE 95). The lightest hybrid nonets are expected in the 1500–2000 MeV mass range in the flux tube model and the ground state around 2000 MeV in lattice gauge theories (LACOCK 97). Charm hybrids ($c\overline{c}g$) are expected in the 4000–4400 MeV mass range and are attractive experimentally since they may appear as supernumerary states in the predictable charmonium spectrum.

Multiquark states might exist as a colour-singlet configuration of four or more quarks. A four-quark state can be either baglike ($qq\overline{q}\overline{q}$) or like a meson-meson bound state ($q\overline{q}$-$q\overline{q}$). Several well-established non-$q\overline{q}$ candidates have masses close to meson-meson thresholds. Examples include the $f_0(980)$ (close to the $K\overline{K}$ threshold), the $f_1(1420)$ ($K\overline{K}^*$), the $f_2(1565)$ and $f_0(1500)$($\omega\omega$ and $\rho\rho$), the $f_J(1710)$ ($K^*\overline{K}^*$), and the $\psi(4040)$ ($D^*\overline{D}^*$).

The following discussion is restricted to well-established resonances which 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 summarize the observations of possible relevance. See also the corresponding Note in the 1996 issue of *Review of Particle Physics.*

Resonances with exotic quantum numbers

The first direct evidence for a non-$q\overline{q}$ state is the exotic $J^{PC} = 1^{-+}$ isovector resonance $\hat{\rho}(1405)$. It has been clearly observed in $\overline{p}d$ annihilation at rest (ABELE 98B), corroborating earlier evidence from πp scattering experiments (ALDE 88B, THOMPSON 97). The $\hat{\rho}(1405)$ is observed as a resonant $(\eta\pi^-)$ P-wave with a width of 200–300 MeV. There is weaker evidence for a $J^{PC} = 1^{-+}$ state around 1900 MeV (LEE 94).

The mass of the $\hat{\rho}(1405)$ is lower than expected by the flux tube model and lattice gauge theories for a hybrid meson, and its decay into two S-wave mesons does not correspond to the expected hybrid decay pattern. A 1^{-+} hybrid around 1400 MeV is, however, predicted by the bag model (BARNES 83). Whatever the correct interpretation will be (hybrid or four-quark state), it is expected to be part of a multiplet in the same mass region, and its identification will be an important goal for future experiments.

A resonance-like structure has been observed in $\gamma\gamma$ collisions near the $\rho\rho$ threshold, decaying into $\rho^0\rho^0$ and $\rho^+\rho^-$, and with a dominating 2^{++} partial wave. The small relative branching ratio $\rho^+\rho^-/\rho^0\rho^0$ (1:4) (ALBRECHT 91F) requires both $I = 0$ and $I = 2$ for the $\rho\rho$ system, which might be due to the presence of a $qq\overline{q}\overline{q}$ resonance with $I = 2$ (ACHASOV 90).

Scalar glueball

Four isoscalar resonances with $J^{PC} = 0^{++}$ are considered as well-established: the σ or $f_0(400–1200)$, a very broad structure with a width of 600–1000 MeV, the $f_0(980)$, the $f_0(1370)$, and the $f_0(1500)$. Another isoscalar, the $f_J(1710)$, may have spin $J = 0$ or 2.

In the quark model, one expects two scalar nonets ($1\ ^3P_0$ and $2\ ^3P_0$) below 2000 MeV. However, the spectrum of scalar $q\overline{q}$ resonances may be strongly distorted by the opening of inelastic thresholds (TORNQVIST 96). For a detailed discussion, see the Note on scalar mesons under the $f_0(1370)$.

Several models interpret the $f_0(1500)$ as a supernumerary scalar state due to a glueball mixed with $q\overline{q}$ states in the same mass region (see for example AMSLER 96). This is based on the observation that both the $f_0(1370)$ and the $f_0(1500)$ have similar decay properties (mainly to light quarks), while the quark model expects the heavier resonance to couple strongly to strange quarks. The $f_0(1500)$ has been observed in 4π (ABELE 96), 2π (AMSLER 95B, BERTIN 98), $\eta\eta$ (AMSLER 95C), $\eta\eta'(958)$ (AMSLER 94E), and—weakly—in $K\overline{K}$ decays (ABELE 96B). The $f_0(1500)$ is observed in gluon-rich reactions, such as central production (ALDE 88, BARBERIS 97B), and in radiative $J/\psi(1S)$ decay, while it is not seen in gamma-gamma fusion (ACCIARRI 95J).

The key issue is the identification of the $^3P_0$ ($s\overline{s}$)-like state in the 1600–2000 MeV mass region. This might be the $f_J(1710)$, if spin 0 is confirmed. In radiative $J/\psi(1S)$ decays, both spin 0 and spin 2 components are found in the $f_J(1710)$ mass region, while the resonance observed in central production has spin 2. An $f_0(1710)$ has also been suggested for the ground state scalar glueball (SEXTON 95). See the Note on $f_J(1710)$.

Tensor glueball

The two1 $^3P_2$ $q\overline{q}$ states are very likely the $f_2(1270)$ and $f_2'(1525)$. In the 1800–2400 MeV mass range, one expects three more tensor nonets: the $2\ ^3P_2$ and $3\ ^3P_2$ radial excitations, and the $1\ ^3F_4$ nonet, i.e. six isoscalar 2^{++} resonances. They are all expected to have widths above 100 MeV. There is indeed evidence for several broad resonances in the 1800–2400 MeV region, but the experimental information is too sparse to make a meaningful assignment to $q\overline{q}$ nonets. There is at present no compelling reason to assume that any of these states is a non-$q\overline{q}$ state.

Two states below 2000 MeV, the $f_2(1565)$ and the $f_J(1710)$, are hard to accommodate in the quark model, because their masses are too close to the $1\ ^3P_2$ ground state to be members of the $2\ ^3P_2$ nonet. The $f_2(1565)$ has only been observed in $p\overline{p}$ annihilation, decaying to $\pi\pi$ (MAY 90, BERTIN 98). The proximity of the $\rho\rho$ and $\omega\omega$ thresholds suggest a possible interpretation as a meson-meson bound state. The $f_J(1710)$ has a well-established 2^{++} component. It is prominently observed in radiative $J/\psi(1S)$ decays, and in central production. It is observed to decay into $K\overline{K}$ (BAI 96C, LONGACRE 86), and its proximity to the $K^*\overline{K}^*$ threshold suggests again a meson-meson bound state.

The narrow $f_2(2220)$ still needs confirmation. There are also still doubts whether it has spin 2 or spin 4. The experimental evidence from $J/\psi(1S)$ radiative decays, πp and Kp scattering is inconclusive. It has not been observed in $p\overline{p}$ annihilation (BARNES 93). If it exists, it couples mainly to strange quark final states, and if spin 2 is confirmed, its prominence in radiative $J/\psi(1S)$ decays and its small width would make it a good glueball candidate.

Pseudoscalar mesons

Four pseudoscalar $I = 0$ resonances are well established below 1500 MeV: η, $\eta'(958)$, $\eta(1295)$, and $\eta(1440)$. It would be natural to identify the latter two with the $u\overline{u} + d\overline{d}$ and $s\overline{s}$ first radial excitations and $s\overline{s}$ of the $^1S_0$ ground states. Since the $\pi(1300)$ and the $\eta(1295)$ have nearly the same masses, the $\eta(1295)$ can be assigned to the $(u\overline{u}+d\overline{d})\ 2\ ^1S_0$ state. The crucial issue is the identification of the $(s\overline{s})\ 2\ ^1S_0$ state. An assignment to the $\eta(1440)$ is not evident. The $\eta(1440)$ is prominently produced in radiative $J/\psi(1S)$ decays and hence expected to have some glueball admixture, and it is mainly produced in $s\overline{s}$ depleted reactions, such as πp scattering, $p\overline{p}$ annihilation, or radiative $J/\psi(1S)$ decays. There is—albeit weak—evidence that the $\eta(1440)$ is made of two resonances with only about 50–100 MeV difference in mass, and with similar widths, the lower mass state decaying to $a_0(980)\pi$ and $\eta\pi\pi$, the higher mass state to $K^*\overline{K}$. It is therefore conceivable that the higher mass state is the $s\overline{s}$ member of the 2 $^1S_0$ nonet (see the Note on $\eta(1440)$).

The $\pi(1800)$ is surprisingly narrow (if interpreted as the second radial excitation of the π). It decays frequently via a pair of S- and P-wave mesons (AMELIN 95B, 96B), which is a signature expected for a hybrid meson.

Axial-vector mesons

The $f_1(1285)$ and $f_1(1420)$ are the two well-established axial-vector resonances. The $f_1(1510)$ still needs confirmation (see the Note on the $f_1(1510)$ under the $\eta(1440)$). The $f_1(1285)$ has the expected properties of the isoscalar $u\overline{u} + d\overline{d}$ member of a ground state $^3P_1$ nonet. The $f_1(1420)$ has a dominant $K\overline{K}^*$ coupling, as expected for the corresponding $s\overline{s}$ member. In πp scattering, $p\overline{p}$ annihilation at rest from P waves (BERTIN 97) and radiative $J/\psi(1S)$ decays, the $f_1(1420)$ is produced together with the $\eta(1440)$, which gave rise to the former E/ι puzzle. In central production, only the $f_1(1420)$ state is produced (BARBERIS 97C).

Presently, there is no strong evidence for an exotic axial-vector state. However, if the $f_1(1510)$ state is corroborated, the proximity of the $f_1(1420)$ mass to the KK^* threshold suggests a $K\overline{K}^*$ meson-bound state or a threshold enhancement.