NON-$q\overline{q}$ MESONS

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The constituent quark model describes the observed meson spectrum as bound $q\overline{q}$ states grouped into SU(N) flavor multiplets (see our review on the quark model). However, 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 such as $qq\overline{q}\overline{q}$ (tetraquark and "molecular" bound states of two mesons) or $qqq\overline{q}\overline{q}\overline{q}$ (six-quark and "baryonium" bound states of two baryons) have also been predicted. For a more detailed discussion on exotic mesons we refer to `AMSLER 04`.

1. Glueball candidates

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(N) predictions for $q\overline{q}$ states, and (iv) reduced $\gamma\gamma$ couplings. However, mixing effects with isoscalar $q\overline{q}$ mesons (`AMSLER 96`, `TORNQVIST 96`, `ANISOVICH 97`, `BOGLIONE 97`, `LEE 00`, `MINKOWSKI 99`, `CLOSE 01B`) and decay form factors (`BARNES 97`) obscure these simple signatures.

Lattice calculations, QCD sum rules, flux tube, and constituent glue models agree that the lightest glueballs have quantum numbers $J^{PC} = 0^{++}$ and 2^{++}. Lattice calculations predict for the ground state, a 0^{++} glueball, a mass around 1650 MeV (`MICHAEL 97`, `LEE 00`, `CHEN 06`) with an uncertainty of about 100 MeV, while the first excited state (2^{++}) has a mass of about 2300 MeV. Hence, the low-mass glueballs lie in the same mass region as ordinary isoscalar $q\overline{q}$ states, in the mass range of the $1^3P_0(0^{++})$, $2^3P_2(2^{++}), 3^3P_2(2^{++})$, and $1^3F_2(2^{++})$ $q\overline{q}$ states. The 0^{-+} state and exotic glueballs (with non-$q\overline{q}$ quantum numbers such as 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, *etc.*) are expected above 2 GeV (`CHEN 06`). 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 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.

We deal here with glueball candidates in the scalar sector. For the 2^{++} sector we refer to the section on non - $q\bar{q}$ mesons in the 2004 issue of this *Review* and for the 0^{-+} glueball to the note on "The $\eta(1405)$, $f_1(1420)$ and $f_1(1510)$" in the Meson Particle Listings.

Five isoscalar resonances are well established: the very broad $f_0(600)$ (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 $f_0(1370)$ and $f_0(1500)$ decay mostly into pions (2π and 4π) while the $f_0(1710)$ decays mainly into $K\overline{K}$ final states. Naively, this suggests an $n\bar{n}$ ($= u\bar{u} + d\bar{d}$) structure for the $f_0(1370)$ and $f_0(1500)$, and $s\bar{s}$ for the $f_0(1710)$. The latter is not observed in $p\overline{p}$ annihilation (AMSLER 02), as expected from the OZI suppression for an $s\overline{s}$ state.

However, in $\gamma\gamma$ collisions leading to $K_S K_S$ (ACCIARRI 01H) and K^+K^- (ABE 04), a spin 0 signal is observed at the $f_0(1710)$ mass (together with a dominant spin 2 component), while the $f_0(1500)$ is not observed in $\gamma\gamma \to K\bar{K}$ nor $\pi^+\pi^-$ (BARATE 00E). The upper limit from $\pi^+\pi^-$ excludes a large $n\overline{n}$ content, and hence would point to a mainly $s\overline{s}$ content for the $f_0(1500)$ (AMSLER 02B). This is in contradiction with the small $K\overline{K}$ decay branching ratio of the $f_0(1500)$ (ABELE 96B,98, BARBERIS 99D). Hence, the $f_0(1500)$ is hard to accommodate as a $q\bar{q}$ state. This state could be mainly glue due its absence of 2γ-coupling, while the $f_0(1710)$ coupling to 2γ would be compatible with an $s\bar{s}$ state. However, the 2γ-couplings are sensitive to glue mixing with $q\bar{q}$ (CLOSE 05).

Since $f_0(1370)$ does not couple strongly to $s\overline{s}$ (BARBERIS 99D), $f_0(1370)$ or $f_0(1500)$ appear to be supernumerary.The narrow width of $f_0(1500)$, and its enhanced production at low transverse momentum transfer in central collisions (CLOSE 97,98B, KIRK 00) also 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 $f_0(1710)$. The isoscalars $f_0(1370)$ and $f_0(1710)$ contain a small fraction of glue, while $f_0(1500)$ is mostly gluonic.

The light scalars $f_0(600)$, $f_0(980)$, $a_0(980)$, and $\kappa(800)$ are four-quark states or two-meson resonances (see AMSLER 04 for a review). In the mixing scheme of CLOSE 05, which uses central production data from WA102 and the recent hadronic J/ψ decay data from BES (ABLIKIM 04E, 05), glue is shared between $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. The $f_0(1370)$ is mainly $n\bar{n}$, the $f_0(1500)$ mainly glue and the $f_0(1710)$ dominantly $s\bar{s}$. This agrees with previous analyses (AMSLER 96, CLOSE 01B), but, as pointed out already, alternative schemes have been proposed (e.g. LEE 00). In particular, for a scalar glueball, the two-gluon coupling to $n\bar{n}$ appears to be suppressed by chiral symmetry (CHANOWITZ 05) and therefore $K\bar{K}$ decay could be enhanced.

Whether the $f_0(1500)$ is observed in gluon rich radiative J/ψ decay is debatable, since data are statistically limited and a proper K-matrix analysis cannot be performed. Hence more data are needed in radiative J/ψ decay and in $\gamma\gamma$ collisions to clarify the spectrum of scalar mesons.

2. Tetraquark candidates and molecular bound states

The $a_0(980)$ and $f_0(980)$ could be four-quark states (JAFFE 77, ALFORD 00) 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 is radiative $\phi(1020)$ decay to $a_0(980)$ and $f_0(980)$. Data from DAPHNE (ALOISIO 02C, 02D) and VEPP - 2M (AKHMETSHIN 99B, ACHASOV 00F) favor these mesons to be four-quark states. In CLOSE 02B they are made of a four-quark core and a virtual $K\bar{K}$ cloud at the periphery. The $f_0(980)$ is strongly produced in D_s^+ decay (AITALA 01A). This points to a large $s\overline{s}$ component, assuming Cabibbo favored $c \to s$ decay. However, the mainly $n\bar{n}$ $f_0(1370)$ is also strongly produced in D_s^+ decay, indicating that other graphs must contribute (CHENG 03B).

Two very narrow states, $D_{s0}^*(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$, were observed at the B-factories (AUBERT 03G, BESSON 03). They lie far below the predicted masses for the two expected broad P-wave $c\overline{s}$ mesons. These states have hence been interpreted as four-quark states (CHENG 03C, TERASAKI 03) or DK (DK^*) molecules (BARNES 03). However, strong cusp effects due to the nearby closed DK, respectively DK^* thresholds, could shift their masses downwards and quench the observed widths, an effect similar to that occuring for the $a_0(980)$ and $f_0(980)$ mesons, which lie just below $K\overline{K}$ threshold.

The search for multiquark states containing a c (or a b) quark is promising since the charmonium spectrum can be predicted accurately, and because some of these states should be narrow if they lie below the $D\bar{D}$ or $D\bar{D}^*$ thresholds. Several states have been observed recently in the charmonium region. The $X(3872)$ was observed in $B^{\pm}$ decays to $K^{\pm}X$, $X \to J/\psi\pi^+\pi^-$, first by BELLE (CHOI 03) and then by BABAR (AUBERT 05R). The state was confirmed by CDF and D0 (ACOSTA 04, ABAZOV 04F) in $\bar{p}p \to J/\psi\pi^+\pi^-$. The known $L = 2$ orbital excitations of charmonium are the $^3D_1$ $\psi(3770)$ and its first radial, the $\psi(4169)$. The $X(3872)$ would be a natural candidate for the $^1D_2$ (2^{-+}) or $^3D_2$ (2^{--}) $c\bar{c}$ states which are expected to be narrow since they cannot decay to $D\bar{D}$. However, its mass is significantly higher than predicted by potential models (see *e.g.*, BARNES 04, EICHTEN 04). However, BELLE has recently established $C = +1$ by observing the decay mode $X(3872) \to \omega J/\psi$ and $\gamma J/\psi$ (hep-ex/0505037). The angular and invariant mass distributions of the dipion in $X(3872) \to \pi^-\pi^- J/\psi$ favor the intermediate state $\rho^0 J/\psi$ and therefore 1^{++} (hep-ex/0505038) (the quantum numbers 2^{++} cannot be entirely ruled out, but are unlikely since the decay $D^0\bar{D}^0\pi^0$ would be suppressed by the angular momentum barrier).

The $X(3872)$ can hardly be identified with the 2^3P_1 χ'_{c1} since this state is predicted to lie about 100 MeV higher in mass (BARNES 04). In fact, the $X(3940)$ observed by BELLE in $e^+e^- \to J/\psi X$, decaying to $D^*\bar{D}$ but not $D\bar{D}$ (hep-ex/0507019) and in B decays to $K(X \to \omega J/\psi)$ (CHOI 05) could be the χ'_{c1}. The tensor partner 2^3P_2 (χ'_{c2}) was reported by BELLE at 3931 MeV in $\gamma\gamma$ interactions (UEHARA 06).

The $X(3872)$ occurs exactly at the $D^0\bar{D}^{*0}$ threshold and therefore the most natural explanation for this state is a 1^{++}

$D\bar{D}^*$ molecule (TORNQVIST 04) for which strong isospin breaking was predicted (TORNQVIST 04, SWANSON 04A) due to the nearby D^+D^{*-} threshold. Indeed, the rates for $\omega J/\psi$ and $\rho^0 J/\psi$ are comparable, which points to isospin mixing. A four-quark state $cq\bar{c}\bar{q}'$ is also possible (MAIANI 05), but unlikely since the charged partner $X(3872)^-$ has not been observed in B^- decays to $\bar{K}^0 X^-$ nor $B^0 \to K^+ X^-$, where $X^- \to J/\psi\pi^-\pi^0$ (AUBERT 05B).

3. Baryonia

Bound states of two nucleons have been predicted, but have remained elusive. The $f_2(1565)$ which is only observed in $\overline{p}p$ annihilation (MAY 90, BERTIN 98) is a good candidate for a 2^{++} $\bar{p}p$ bound state. Enhancements in the $\bar{p}p$ mass spectrum have also been reported around 1860 MeV, just below $\bar{p}p$ threshold, in $J/\psi \to \gamma\bar{p}p$ (BAI 05F) and in $B^+ \to K^+\bar{p}p$, $B^0 \to K^0_S\bar{p}p$ (ABE 02K, WANG 05A) and $\bar{B}^0 \to D^0\bar{p}p$ (ABE 02W). This enhancement could be due to a 0^{-+} baryonium (DING 05) but other explanations have been proposed, such as dynamics of the fragmentation mechanism (WANG 05A) or the attractive $^1S_0$ $(\bar{p}p)$ -wave (LOISEAU 05).

4. Hybrid mesons

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 $\pm$ 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, $\pi_1(1400)$, was reported in $\pi^- p \to \eta\pi^- p$ (THOMPSON 97, CHUNG 99). 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). Mass and width are consistent with THOMPSON 97.

Another 1^{-+} state, $\pi_1(1600)$, decaying into $\rho\pi$ (ADAMS 98B), $\eta'\pi$ (IVANOV 01), $f_1(1285)\pi$ (KUHN 04), and $\omega\pi\pi$ (LU 05) was reported in $\pi^- p$ interactions. 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 suggests that a Deck-generated $\eta\pi$ background from final state rescattering in $\pi_1(1600)$ decay could mimic $\pi_1(1400)$. 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). Finally, evidence for a $\pi_1(2015)$ has also been reported (KUHN 04 , LU 05).

Thus, we now have at least 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. 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 (see also CHUNG 02C), while the strong $\eta'\pi$ coupling of the latter is favored for hybrid states (CLOSE 87B, IDDIR 01). Its mass is not far below the lattice prediction.

Hybrids with $J^{PC} = 0^{-+}$, 1^{--}, and 2^{-+} have also been 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. This meson is also rather narrow if interpreted as the second radial excitation of 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).

Finally, a broad structure $Y(4260)$ was reported by BABAR (AUBERT, B 05I) in initial state radiation $e^+e^- \to \gamma e^+e^-$ where $e^+e^- \to Y(4260) \to J/\psi\pi^+\pi^-$. A charmonium state with the quantum numbers 1^{--} is not expected in this mass region. This state could be a hybrid charmonium (CLOSE 05A, KOU 05), but also a four-quark state (MAIANI 05A). It is possibly also seen in B^- decays to $K^- J/\psi\pi^+\pi^-$ (AUBERT 06).