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 $s\overline{s}$ 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_SK_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).