96. Non-$q\overline{q}$ Mesons

Revised August 2019 by C. Amsler (Stefan Meyer Inst.) and C. Hanhart (Jülich).

The constituent quark model describes the observed meson spectrum as bound $q\overline{q}$ states grouped into SU(N) flavor multiplets (see the 'Quark Model' in this issue of the *Review of Particle Physics*). 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. Furthermore, multiquark color singlet states such as $qq\overline{q}\overline{q}$ (tetraquarks as compact diquark-antidiquark systems and 'molecular' bound states of two mesons) or $qqq\overline{q}\overline{q}\overline{q}$ (six-quark and 'baryonium' states of two baryons) have also been predicted.

In recent years experimental evidence for states beyond the quark model has accumulated in the heavy quark sector and elsewhere. We therefore split our review into three parts discussing separately light systems, heavy–light systems and heavy–heavy systems. For a more detailed discussion on exotic mesons we refer to [1] for the light meson sector and [2, 3] for the heavy meson sector. Reviews with main focus on tetraquarks and molecular states are presented in [4] and [5], respectively. For an experimental status with focus on the heavy quark sector see [6].

96.1 Light systems

96.1.1 *Glueball candidates*

Among the signatures naively expected for glueballs are (i) isoscalar states that do not fit into $q\overline{q}$ 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 [7–15] and decay form factors [16] can 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 (0^{++}) a mass around 1600 – 1700 MeV [12, 17–19] with an uncertainty of about 100 MeV, while the first excited state (2^{++}) has a mass of about 2300 MeV. Hence, the light 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. Heavier glueballs with quantum numbers 0^{-+}, 2^{-+}, 1^{+-}, ... are predicted above 2500 MeV (the 1^{+-} being at least as broad as its width in holographic QCD [20]) and the lowest exotic ones (with non-$q\overline{q}$ quantum numbers such as 0^{+-} and 2^{+-}) are expected above 4000 MeV [19]. The lattice calculations were performed so far in the quenched approximation. Thus neither quark loops nor mixing with conventional mesons were included, although quenching effects seem to be small [21]. (For a recent comparison between quenched and unquenched lattice studies see [22].) The mixing of glueballs with nearby $q\overline{q}$ states of the same quantum numbers should lead to a supernumerary isoscalar state in the SU(3) classification of $q\overline{q}$ mesons. A lattice study in full QCD (performed at unphysical quark masses corresponding to a pion mass of 400 MeV) did not identify states with sizeable overlap with pure gluonic sources [23, 24].

In the following we focus on glueball candidates in the scalar sector. For the 2^{++} sector we refer to the section on non-$q\overline{q}$ mesons in the 2006 issue of the *Review* [25], and for the 0^{-+} glueball to the note on 'The Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region' in the *Meson Listings* of the *Review*.

Five isoscalar resonances are established: the very broad $f_0(500)$ (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 below 2 GeV' in the *Meson Listings*, and also [26]. Their isospin $\frac{1}{2}$ and isovector partners are the $K_0^*(700)$ (or κ), the $K_0^*(1430)$, the $a_0(980)$ and the $a_0(1450)$. However, none of the proposed

$q\bar{q}$ ordering schemes in scalar multiplets is entirely satisfactory. 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 last state is not observed in $p\overline{p}$ annihilation [27], as expected from the OZI suppression for an $s\overline{s}$ state.

In $\gamma\gamma$ collisions leading to $K_S K_S$ [28] and K^+K^- [29] 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 $\pi^+\pi^-$ [30]. The $f_0(1500)$ is also not observed by Belle in $\gamma\gamma \to \pi^0\pi^0$, although a shoulder is seen which could also be due to the $f_0(1370)$ [31]. The absence of a signal in the $\pi\pi$ channel in $\gamma\gamma$ collisions does not favor an $\overline{n}n$ interpretation for the $f_0(1500)$. The upper limit from $\pi^+\pi^-$ excludes a large $n\overline{n}$ content, and hence points to a mainly $s\overline{s}$ content [32]. This is in contradiction with the small $K\overline{K}$ decay branching ratio of the $f_0(1500)$ [33–35]. This state could be mainly glue due its absence of $\gamma\gamma$ coupling, while the $f_0(1710)$ coupling to $\gamma\gamma$ would be compatible with an $s\bar{s}$ state. Indeed, Belle finds that in $\gamma\gamma \to K_S K_S$ collisions the 1500 MeV region is dominated by the $f_2'(1525)$. The $f_0(1710)$ is also observed but its production $\times$ decay rate is too large for a glueball [36]. However, the $\gamma\gamma$ couplings are sensitive to glue mixing with $q\bar{q}$ [37].

Since the $f_0(1370)$ does not couple strongly to $s\overline{s}$ [35], the $f_0(1370)$ or $f_0(1500)$ appear to be supernumerary. The narrow width of the $f_0(1500)$, and its enhanced production at low transverse momentum transfer in central collisions [38–40] also favor the $f_0(1500)$ to be non-$q\overline{q}$. In [7] the ground state scalar nonet is made of the $a_0(1450)$, $f_0(1370)$, $K_0^*(1430)$, and $f_0(1710)$. The isoscalars $f_0(1370)$ and $f_0(1710)$ contain a small fraction of glue, while the $f_0(1500)$ is mostly gluonic (see also [13]). The light scalars $f_0(500)$, $f_0(980)$, $a_0(980)$, and $K_0^*(700)$ are four-quark states or two-meson resonances, see [1] for a review and [41] which focuses on the $f_0(500)$. In the mixing scheme of Ref. [37], which uses central production data from WA102 and the hadronic J/ψ decay data from BES [42, 43], glue is shared between the $f_0(1370)$, $f_0(1500)$ 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 [7, 13], but, as already pointed out, alternative schemes have been proposed [7–15], in particular with the $f_0(1710)$ as the glueball [44, 45] or the $f_0(1500)$ as a tetraquark [46].

For a scalar glueball the two-gluon coupling to $n\bar{n}$ appears to be suppressed by chiral symmetry [47] and therefore $K\bar{K}$ decay could be enhanced. However, $K\bar{K}$ is naturally enhanced also in the extended linear sigma model with a dilaton as glueball [44] and in the holographic model of [45]. It was argued that chiral symmetry constraints in a multichannel analysis imply that the $f_0(1710)$ is an unmixed scalar glueball [48], a view that is challenged in [49].

Different mixing options have been studied in [15]. In the preferred solution the ground state scalar nonet consists of the $f_0(980)$, $a_0(980)$, $K_0^*(1430)$, $f_0(1500)$ and $f_0(1710)$. The $f_0(980)$ and $f_0(1500)$ mix similarly to the η and η' in the pseudoscalar nonet, while the $f_0(1500)$ mixes with a glueball in the $500 - 1000$ MeV mass range, which is identified with the $f_0(500)$ (σ). A reanalysis of the CERN-Munich data shows no signal for the $f_0(1370)$ decaying into $\pi\pi$, in contrast to [50]. However, in this scheme the $K_0^*(700)$ (κ) and the $a_0(1450)$ are left out (see also our note on 'Scalar Mesons below 2 GeV' in the *Meson Listings*). The $a_0(1450)$ has recently been confirmed by LHCb data in $D^0 \to K_S^0 K^\pm \pi^\mp$ [51].

The $f_0(1370)$ is also not needed in the COMPASS $\pi^- p \to \pi^-\pi^-\pi^+ p$ data [52], which questions its mere existence. However, a recent analysis from CLEO-c on $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decay requires a contribution from $f_0(500)f_0(1370) \to 4\pi$ [53].

The Dalitz plots of $B^\pm \to \pi^\pm\pi^\pm\pi^\mp$ have been studied by BaBar [54]. A broad 2π signal is observed around 1400 MeV which is attributed to the $f_0(1370)$, but could also be due to the $f_0(1500)$. LHCb has analyzed $\overline{B}^0$ decay into $J/\psi\,\pi^+\pi^-$ [55]. The fit to the $\pi\pi$ mass spectrum above

$\sim$1.2 GeV does not show any significant scalar component. However, the data analysis has been challenged [56]. For $\overline{B}^0_s \to J/\psi\,\pi^+\pi^-$ a strong scalar contribution from the $f_0(1370)$ is found [57]. Following the suggestion in Ref. [15], new data for the same reaction were analyzed by introducing instead the $f_0(500)$ and $f_0(1500)$ without any need for the $f_0(1370)$ [58]. This conclusion does not change when improved theoretical tools, as well as the data from [59] on $\overline{B}^0_s \to J/\psi\,K\bar{K}$, are employed in the analysis [60].

In $B^{\pm} \to K^{\pm}K^{\pm}K^{\mp}$ both BaBar [61] and Belle [62] observe a strong spin-0 activity in $K\bar{K}$ around 1550 MeV. The decay $B \to J/\psi X$ filters out the $d\overline{d}$ content of X while $B^0_s \to J/\psi X$ selects its $s\overline{s}$ component. These decays may therefore be ideal environments to determine the flavor contents of neutral mesons [63].

The contribution of $f_0(1500)$ production in (the supposedly gluon rich) radiative J/ψ decay is not well known. The $f_0(1500)$ is observed by BESII in $J/\psi \to \gamma\pi\pi$ [64] and by BESIII in $J/\psi \to \gamma\eta\eta$ [65] with a much smaller rate than for the $f_0(1710)$, which speaks against a glueball interpretation for the former. However, the $f_0(1500)$ mass found by BES is significantly lower than the expected value. The overlap with the $f_0(1370)$ and $f_2'(1525)$, and the statistically limited data sample, prevent a proper K-matrix analysis to be performed. Hence more data are needed in radiative J/ψ decay and in $\gamma\gamma$ collisions to clarify the spectrum of scalar mesons.

96.1.2 *Tetraquark candidates and molecular bound states*

The existence of multiquark states was suggested a long time ago based on duality arguments [66], see also [67]. The $a_0(980)$ and $f_0(980)$ could be tetraquark states [68–70] or $K\overline{K}$ molecular states [71–73] due to their large branching ratios into $K\overline{K}$, in spite of their masses being very close to threshold, leaving very little phase space. For $q\overline{q}$ states, the expected $\gamma\gamma$ widths [74, 75] are not significantly larger than for molecular states [74, 76], both predictions being consistent with data. Radiative decays of the $\phi(1020)$ into $a_0(980)$ and $f_0(980)$ were claimed to enable disentangling compact from molecular structures. Interpreting the data from DAϕNE [77, 78] and VEPP-2M [79, 80] along the lines of [81, 82] seems to favor these mesons to be tetraquark states. In Ref. [83] they are made of a four-quark core and a virtual $K\bar{K}$ cloud at the periphery. This is challenged in [84] which shows that ϕ radiative decay data are consistent with molecular structures of the light scalars. The $f_0(980)$ is strongly produced in D_s^+ decay [85], which 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 [86].

Ratios of decay rates of B and/or B_s mesons into $J/\psi f_0(980)$ or $J/\psi f_0(500)$ were proposed to extract the flavor mixing angle and to probe the tetraquark nature of those mesons within certain models [87,88]. The phenomenological fits of LHCb, based on an isobar model, do neither allow for a contribution of the $f_0(980)$ in the $B \to J/\psi\pi\pi$ [55] nor for an $f_0(500)$ in $B_s \to J/\psi\pi\pi$ decays [58]. Hence the authors conclude that their data are incompatible at the eight standard deviation level with a model in which the $f_0(500)$ and $f_0(980)$ are tetraquarks. They also extract an upper limit for the mixing angle of 17^o between the $f_0(980)$ and the $f_0(500)$ that would correspond to a substantial $\bar{s}s$ content in the $f_0(980)$ [58]. However, in a dispersive analysis [89] of the same data that allows for a model independent inclusion of the hadronic final state interactions, a substantial $f_0(980)$ contribution is also found in the B-decays, thus putting into question the conclusions in [58].

COMPASS reports a new 1^{++} isovector meson decaying into $f_0(980)\pi$, the $a_1(1420)$ [90,91]. The resonance is observed in diffractive dissociation $\pi^- p \to \pi^-(\pi^+\pi^-)p$. Traditionally, the 1^{++} ground state nonet is believed to contain the $a_1(1260)$, $f_1(1285)$ and $f_1(1420)$ (see 'The Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region' in the *Meson Listings*). A molecular $K\overline{K}\pi$ structure has been proposed for the $f_1(1420)$ [92] in view of the proximity of the $K^*\overline{K}$ threshold. The new $a_1(1420)$ could also be a molecular state, the isovector partner of the $f_1(1420)$. However, according to [93], the $f_1(1420)$ may not exist, being a manifestation of the $f_1(1285)$ due to a triangle singularity. Ref. [94] also explains the $a_1(1420)$ as the signature of the $a_1(1260)$ distorted by a triangle singularity.

96.1.3 *Baryonia*

Bound states of a baryon and an antibaryon have been predicted in the past [95, 96], but have remained elusive. The $f_2(1565)$ which is only observed in $\bar{p}p$ annihilation [97, 98] is a good candidate for a 2^{++} $\bar{p}p$ bound state. Enhancements close to the $\bar{p}p$ threshold have been reported in $B^+ \to K^+\bar{p}p$, $B^0 \to K^0_S\bar{p}p$ [99, 100], $\bar{B}^0 \to D^0\bar{p}p$ [101], $e^+e^- \to \bar{p}p$ [102, 103], $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to e^+e^-$ [104]. The spectacular signal seen in $J/\psi \to \gamma\bar{p}p$ [105–107] could be due to a 0^{-+} baryonium [108]. Such a pole is not necessarily a compact $qqq\bar{q}\bar{q}\bar{q}$ state, but might be generated via non-perturbative nucleon-antinucleon final state interactions [109–112]. Also the structures visible in various data sets for $e^+e^- \to n\pi$ [113,114] near the $\bar{p}p$ threshold appear to be largely explained by the same nucleon–antinucleon final state interactions [115]. However, other explanations have also been proposed to explain e.g. the signals in $B \to \bar{p}pK$, such as the dynamics of the fragmentation mechanism [100].

The pronounced signal observed by Belle in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ around $\sqrt{s} = 4.63$ GeV [116] was argued to be a strong evidence in favor of an interpretation of $Y(4660)$ as charmed baryonium [117]. However, this picture was challenged in Refs. [118, 119].

96.1.4 *Hybrid mesons*

Hybrids may be viewed as $q\bar{q}$ mesons with a vibrating gluon flux tube. In contrast to glueballs, they can have isospin 0 or 1. The mass spectrum of hybrids with exotic (non-$q\bar{q}$) quantum numbers was predicted in [120], while [121] 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 ± 0.2 GeV [122, 123]. Most hybrids are expected to be rather broad, but some can be as narrow as 100 MeV [124]. They prefer to decay into a pair of S- and P-wave mesons. The lattice study in [23, 125], based on full QCD with pion masses around 400 MeV, finds that several of the high-lying states observed in their spectrum show significant overlap with gluon rich source terms interpreted as hybrid states. For a recent experimental and theoretical review on hybrid mesons see [126].

A $J^{PC} = 1^{-+}$ exotic meson, the $\pi_1(1400)$, was reported in $\pi^-p \to \eta\pi^-p$ [127, 128] and in $\pi^-p \to \eta\pi^0n$ [129]. 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 had been reported earlier in π^-p reactions [130], but ambiguous solutions in the partial wave analysis were pointed out [131, 132]. A resonating 1^{-+} contribution to the $\eta\pi$ P-wave is also required in the Dalitz plot analysis of $\bar{p}n$ annihilation into $\pi^-\pi^0\eta$ [133], and in $\bar{p}p$ annihilation into $\pi^0\pi^0\eta$ [134]. Mass and width are consistent with the results of [127].

Another 1^{-+} state, the $\pi_1(1600)$ decaying into $\rho\pi$, was reported by COMPASS with 190 GeV pions hitting a lead target [135]. It was observed earlier in π^-p interactions in the decay modes $\eta'\pi$ [136], $f_1(1285)\pi$ [137], and $\omega\pi\pi$ [138], $b_1(1235)\pi$, but not $\eta\pi$ [139]. A strong enhancement in the 1^{-+} $\eta'\pi$ wave, compared to $\eta\pi$, was reported at this mass in [140]. Ref. [141] suggested 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 $\bar{p}p$ annihilation. The $\eta\pi\pi$ data require $\pi_1(1400)$ and cannot accommodate a state at 1600 MeV [142]. A coupled channel analysis of the COMPASS data leads to a single pole at 1564 MeV [143].

The flux tube model and the lattice concur to predict a hybrid mass of about 1.9 GeV while the $\pi_1(1400)$ and $\pi_1(1600)$ are lighter. 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 [144], while the strong $\eta'\pi$ coupling of the latter is favored for hybrid states [145, 146]. The mass of $\pi_1(1600)$ is also not far below the lattice prediction.

Evidence for a $\pi_1(2015)$ has also been reported [137, 138]. Hybrid candidates 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 [135, 147], in line with expectations for 0^{-+} hybrid mesons. This meson is also somewhat 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 in [148]. A candidate for the 2^{-+} hybrid, the $\eta_2(1870)$, was reported in $\gamma\gamma$ interactions [149], in $\overline{p}p$ annihilation [150], and in central production [151]. 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 $f_2(1270)\pi$ [150], with a relative rate compatible with a hybrid state [121].

96.2 Heavy-light systems

Two very narrow states, $D^*_{s0}(2317)^\pm$ and $D_{s1}(2460)^\pm$, were observed at B factories [152, 153]. 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 [154–157] or DK (DK^*) molecules [158–162]. However, strong cusp effects, due to the nearby DK (DK^*) thresholds, could shift their masses downwards and quench the observed widths, an effect similar to that claimed for the $a_0(980)$ and $f_0(980)$ mesons, which lie just below $K\overline{K}$ threshold. A hadronic width of typically 100 keV would be the unequivocal signature for a prominent molecular nature of $D^*_{s0}(2317)^\pm$ [160–162]. More compact structures typically produce widths below 10 keV [163, 164]. The currently measured upper bound for the width is 3.8 MeV.

It should be stressed that – akin to $q\overline{q}$ mesons – multiquark states also appear in multiplets. For example, recent studies [165–167] show that, if $D_{s0}(2317)$ were of molecular nature, the lowest non-strange scalar D-state, the $D^*_0(2300)$, would also be molecular in nature, with a two-pole structure (the lower one at 2105 MeV and the upper one at 2451MeV, on different physical sheets, however, see Ref. [165] for details) similar to the $\Lambda(1405)$, see 'Pole structure of the $\Lambda(1405)$ region' in the *Review*. In [166] this assignment is demonstrated to be consistent with recent data from LHCb on $B^- \to D^+\pi^-\pi^-$ [168]. Two poles in the non-strange scalar sector are also generated in the tetraquark picture of Ref. [157], but in this work the real parts of the poles are located at 2308 MeV and 2666 MeV, which should be testable experimentally.

96.3 Heavy-heavy systems

Several unexpected states have been observed in both charmonium and bottomonium regions. With the discovery of the $X(3872)$ in $B^\pm \to K^\pm X$ ($X \to J/\psi\,\pi^+\pi^-$) by Belle [169] in 2003, soon confirmed by BaBar [170], many searches for states beyond the standard quark model were initiated in the charm and in the bottom sectors. For an updated collection of the currently available experimental information on multiquark states we refer to 'Spectroscopy of mesons containing two heavy quarks' in the *Review*. Moreover, in the decay $\Lambda^0_b \to J/\psi\,K^-p$ the LHCb collaboration has recently reported the observation of two new baryons decaying into $J/\psi\,p$, which are candidates for heavy pentaquark states [171]. They are discussed in some depth in 'Pentaquarks' in the *Review*.

When restricting ourselves to confirmed states we are faced with several ones that do not seem to fit into the most simple quark models. This is clear for the six established charged states ($Z_c(3900)^\pm$, $Z_c(4020)^\pm$ [1], $Z_c(4200)^\pm$ and $Z_c(4430)^\pm$ in the charmonium sector, and $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ in the bottomonium sector). The neutral ones ($\chi_{c1}(3872)$ aka $X(3872)$, $\psi(4260)$

[1] While the $J^P = 1^+$ quantum numbers are plausible for this state, they are not yet established experimentally. This is why this state appears as $X(4020)$ in both listings and summary tables.

aka $Y(4260)$, $\psi(4360)$ aka $Y(4360)$, $\psi(4660)$ aka $Y(4660)$) [2] also challenge the quark models since their masses and decay properties are in conflict with expectations.

The quantum numbers of the $X(3872)$ have been determined by LHCb to be $J^{PC} = 1^{++}$, first by assuming the angular momentum zero between the J/ψ and the dipion [172] and then by relaxing this constraint [173]. The $X(3872)$ can hardly be identified with the 2^3P_1 χ'_{c1} since the latter is predicted to lie about 100 MeV higher in mass [174]. Instead, the $X(3940)$ reported by Belle in $e^+e^- \to J/\psi X$, decaying into $D^*\bar{D}$ but not into $D\bar{D}$ [175], and also observed in $B \to K(X \to \omega J/\psi)$ [176] could be the χ'_{c1}. The 2^3P_2 tensor partner (χ'_{c2}) was reported by Belle at 3931 MeV in $\gamma\gamma$ interactions [177].

The $X(3872)$ lies within 200 keV of the $D^0\bar{D}^{*0}$ threshold and therefore the most natural explanation for this state is a 1^{++} $D\bar{D}^*$ molecule [178], for which strong isospin breaking is predicted [178, 179], since the distance of the pole of the $X(3872)$ to the $D^0\bar{D}^{*0}$ threshold is significantly smaller than to the D^+D^{*-} threshold. Indeed, the comparable rates for $\omega J/\psi$ and $\rho^0 J/\psi$ are consistent with an interpretation of $X(3872)$ as an isoscalar $D\bar{D}^*$ molecule when the different widths of the ρ and ω are taken into account [180]. A four-quark state $cq\bar{c}\bar{q}'$ is also possible [156] but unlikely, since the charged partner of the $X(3872)$ has not been observed (e.g. not in $B^- \to \bar{K}^0X^-$ nor in $B^0 \to K^+X^-$, where $X^- \to J/\psi\,\pi^-\pi^0$ [181]) – see [182] for a possible explanation of this non-observation within the tetraquark approach. The claim that $X(3872)$ must be a compact (tetraquark) state, since it is also produced at very high p_T in $\bar{p}p$ collisions [183], was challenged in [184], which stresses the importance of rescattering, see also [185, 186].

A broad structure, $Y(4260)$, decaying into $J/\psi\,\pi^+\pi^-$ was reported by BaBar in initial state radiation $e^+e^- \to \gamma(e^+e^- \to Y(4260))$ [187]. A measurement with significantly improved statistics was recently reported by BESIII [188]. The Breit-Wigner fit of these data leads to a mass reduction of 40 MeV, but also requires a second state at 4320 MeV. However, the $D_1\bar{D}$ molecular model for the $Y(4260)$ [189] is capable to describe the same data with just one single pole [190].

There are no charmonium states expected in this mass region with quantum numbers 1^{--} from quark models using the Cornell type of interaction, although this might not be true for some screened versions thereof – for a recent discussion we refer to Ref. [191]. In addition, a charmonium at this mass should have a significant coupling to $\bar{D}D$, a decay channel that is not observed for the $Y(4260)$. This state could be a hybrid charmonium with a spin-1 $\bar{c}c$ [192, 193] or a spin-0 [194, 195] core. However, provided that the observation of $Y(4260)$ decay into $h_c(1P)\pi\pi$ by BESIII [196] is confirmed, the hybrid hypothesis would be under pressure, since the spin of the heavy quarks (coupled to zero in the $h_c(1P)$) should be conserved in leading order in the expansion in ($\Lambda_{\rm QCD}/m_c$). (The individual conservation of the heavy quark spin and the total angular momentum of the light quark cloud is a consequence of the heavy-quark spin symmetry, see 'Heavy-Quark and Soft-Collinear Effective Theory' in this issue of the *Review*.)

The same criticism applies to the hadrocharmonium interpretation of the $Y(4260)$, which describes this state as spin-1 quarkonium surrounded by a light quark cloud [197]. To circumvent the spin-symmetry argument Ref. [198] argues that $Y(4260)$ and $Y(4360)$ could be mixtures of two hadrocharmonia with spin-triplet and spin-singlet heavy quark pairs. The same kind of mixing could also operate for a hybrid.

A dominant $D_1\bar{D}$ component in the $Y(4260)$ [199] explains naturally why $Z_c(3900)^\pm$ (interpreted by the authors as a $\bar{D}D^*$ bound state) is seen in $Y(4260) \to \pi^\mp Z_c(3900)^\pm$. Furthermore, a copious production of $X(3872)$ in $Y(4260)$ radiative decays was predicted from the prominent $D_1\bar{D}$ component of the $Y(4260)$ [200], which was confirmed by BESIII [201]. The $Y(4360)$ as a

[2] According to the PDG naming scheme the prime name for these states is the quark model name, here listed first for each state, since it expresses the quantum numbers. However, in what follows we use the names mostly used in the literature to ease notations and to avoid confusion.

$D_1\bar{D}^*$ bound state could be the spin partner of the $Y(4260)$ [202, 203], but a detailed microscopic calculation is still lacking.

The tetraquark picture explains the observed Y states [204] and is also capable – when including a tailor-made spin-spin interaction [205] – to describe the $X(3872)$, both $Z_c(3900)^{\pm,0}$ and $Z_c(4020)^{\pm}$ and even the $Z(4430)^{\pm}$ confirmed by Belle [206] and LHCb [207]. The latter reference also determined the quantum numbers of this state to $J^P = 1^+$. However, the model predicts many additional charged and neutral states which have not yet been discovered. A possible explanation can be found in [182].

Ref. [208] found a sizeable SU(3) flavor octet contribution when analysing the $\pi\pi$ final state from $Y(4260) \to J/\psi\pi^+\pi^-$, which is consistent with both a molecular and a tetraquark interpretation of $Y(4260)$, but at odds with a hybrid or a $\bar{c}c$ interpretation.

The charged states $Z_c(3900)^{\pm}$, first observed by BESIII [209] and the $Z_c(4020)^{\pm}$ [210] decay predominantly into $\bar{D}D^*$ and $\bar{D}^*D^*$, respectively, while $Z_b(10610)^{\pm,0}$ and $Z_b(10650)^{\pm}$ [211, 212] decay predominantly into $\bar{B}B^*$ and $\bar{B}^*B^*$ [213], respectively, although all of them were discovered in the decay mode heavy quarkonium plus pion. This suggests that these states are close relatives and their interactions are connected via heavy quark flavor symmetry. A molecular interpretation for the bottomonium states was proposed shortly after the discovery of the $Z_b^{\pm}$ states [214] and also shortly after that of the $Z_c(3900)^{\pm}$ [199]. However, some of their properties also appear to be consistent with tetraquark structures [215]. If the molecular picture were correct for the Z_b states, spin symmetry would lead to the existence of spin partner states [216–218], which are still to be found. In Ref. [219] it was shown that the actual pole locations of those partner states would be good probes of the role of the one-pion exchange in the molecular potential, which makes the experimental search for those states even more interesting.

The heaviest confirmed charged state in the charmonium sector is the $Z(4430)^{\pm}$ observed by Belle [206]. It is interpreted as hadrocharmonium [197], $\bar{D}_1D^*$ molecule [220] as well as tetraquark [205]. Alternatively, in [221, 222] the $Z(4430)^{\pm}$ is explained as a cross-channel effect enhanced by a triangle singularity from open charm states. These works were criticised in Ref. [223] where an alternative triangle consisting of a K^*, a π and the $Y(4260)$ is proposed to generate the $Z_c(4430)$. The Argand diagram shows an anticlockwise circle, in line with the experimental analysis [207], while the one of Ref. [222] shows a clockwise motion. By replacing the $Y(4260)$ by the $\psi(3770)$ and changing the K^* one can also interpret the $Z_c(4200)$ as a kinematic effect [223].

It should be stressed that the various scenarios, while describing the data, also make decisive predictions, e.g. yet unobserved quantum numbers [204, 224]. The forthcoming data on heavy meson spectroscopy from various facilities should provide a much deeper understanding on how QCD forms matter out of quarks and gluons.

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