95. 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' in this issue of the *Review*). 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' bound 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 this minireview 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 Ref. 1 for the light meson sector and Ref. 2 for the heavy meson sector. Reviews with main focus on tetraquarks and molecular states are presented in Ref. 3 and Ref. 4, respectively. For an experimental review see Ref. 5.

95.1. Light systems

95.1.1. ***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 [6–14] and decay form factors [17] 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 (a 0^{++} glueball) a mass around 1600 – 1700 MeV [11,18–20] 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 [20]. 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 Ref. 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 this *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*.

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 Ref. 26. Their isospin 1/2 and isovector partners are the $K_0^*(700)$ (or κ), the $K_0^*(1430)$, the $a_0(980)$ and the $a_0(1450)$. We shall see that 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 latter is not observed in $p\bar{p}$ annihilation [27], as expected from the OZI suppression for an $s\bar{s}$ 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 2γ-coupling, while the $f_0(1710)$ coupling to 2γ 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 2γ-couplings are sensitive to glue mixing with $q\bar{q}$ [37].

Since the $f_0(1370)$ does not couple strongly to $s\bar{s}$ [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-$q\bar{q}$. In Ref. 6 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. 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 Ref. 1 for a review). For a recent review with focus on $f_0(500)$ we refer to Ref. 41. 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 [6,12], but, as already pointed out, alternative schemes have been proposed [6–16].

In particular, for a scalar glueball the two-gluon coupling to $n\bar{n}$ appears to be suppressed by chiral symmetry [44] 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 [15] and in the holographic model of Ref. 16. It was argued that chiral symmetry constraints in a multichannel analysis imply that the $f_0(1710)$ is an unmixed scalar glueball [45], a view that is challenged [46].

Different mixing options have been studied in Ref. 14. 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 Ref. 47. 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 $D^0 \to K_S^0 K^\pm \pi^\mp$ [48].

The $f_0(1370)$ is not needed either in the COMPASS $\pi^- p \to \pi^-\pi^-\pi^+ p$ data [49], 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 $f_0(500)f_0(1370) \to 4\pi$ [50].

The Dalitz plots of $B^\pm \to \pi^\pm\pi^\pm\pi^\mp$ have been studied by BaBar [51]. 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 $J/\psi\,\pi^+\pi^-$ [52]. The fit to the $\pi\pi$ mass spectrum above ~1.2 GeV does not show any significant scalar component. However, the data analysis has been challenged [53]. For $\overline{B}_s^0 \to J/\psi\,\pi^+\pi^-$ a strong scalar contribution from the $f_0(1370)$ is found [54]. Suggested by Ref. 14 the data were reanalyzed by introducing instead the $f_0(500)$ and $f_0(1500)$ [55].

In $B^\pm \to K^\pm K^\pm K^\mp$ both BaBar [56] and Belle [57] observe a strong spin-0 activity in $K\bar{K}$ around 1550 MeV. B^0 decay into $J/\psi X$ filters out the $d\bar{d}$ content of X while B_s^0 decay selects its $s\bar{s}$ component. B decay into $J/\psi X$ may therefore be the ideal environment to determine the flavor content of neutral mesons [58].

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 $J/\psi \to \gamma\pi\pi$ [59] and by BESIII in $J/\psi \to \gamma\eta\eta$ [60] 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.

95.1.2. ***Tetraquark candidates and molecular bound states*** : The $a_0(980)$ and $f_0(980)$ could be tetraquark states [61–63] or $K\overline{K}$ molecular states [64–66] 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 [67,68] are not significantly larger than for molecular states [67,69], 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 DAPHNE [70,71] and VEPP - 2M [72,73] along the lines of Refs. 74,75 seems to favor these mesons to be tetraquark states. In Ref. 76 they are made of a four-quark core and a virtual $K\bar{K}$ cloud at the periphery. This is challenged in Ref. 77 showing that ϕ radiative decay data are consistent with a molecular structure of the light scalars. The $f_0(980)$ is strongly produced in D_s^+ decay [78]. This points to a large $s\bar{s}$ 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 [79].

Ratios of decay rates of B and/or B_s mesons into J/ψ plus $f_0(980)$ or $f_0(500)$ were proposed to allow for an extraction of the flavor mixing angle and to probe the tetraquark nature of those mesons within a certain model [80,81]. The phenomenological fits of the LHCb collaboration based on an isobar model do neither allow for a contribution of the $f_0(980)$ in the $B \to J/\psi\pi\pi$ [52] nor for an $f_0(500)$ in $B_s \to J/\psi\pi\pi$ decays [55]. From these analyses the authors conclude that their data are incompatible with a model where $f_0(500)$ and $f_0(980)$ are tetraquarks at the eight standard deviation level. In addition, they extract an upper limit for the mixing angle of 17^o at 90% C.L. between the $f_0(980)$ and the $f_0(500)$ that would correspond to a substantial $(\bar{s}s)$ content in $f_0(980)$ [55]. However, in a dispersive analysis of the same data that allows for a model–independent inclusion of the hadronic final state interactions in Ref. 82 a substantial $f_0(980)$ contribution is also found in the B–decays putting into question the conclusions of Ref. 55.

COMPASS reports a new 1^{++} isovector meson at 1414 MeV, decaying into $f_0(980)\pi$ [83] (called $a_1(1420)$ in the 2017 Review of Particle Physics). 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 mini-review on 'The Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region' in the *Meson Listings*). However, a molecular $K\overline{K}\pi$ structure has been proposed for the $f_1(1420)$ [84] in view of the proximity of the $K^*\overline{K}$ threshold. The new $a_1(1420)$ could then also be a molecular state, the isovector partner of the $f_1(1420)$. Ref. [85] explains the $a_1(1420)$ not as a state but as signature of the $a_1(1260)$ distorted by a triangle singularity.

95.1.3. *Baryonia* :

Bound states of a baryon and an antibaryon have been predicted, but have remained elusive. The $f_2(1565)$ which is only observed in $\overline{p}p$ annihilation [86,87] is a good candidate for a 2^{++} $\bar{p}p$ bound state. Enhancements in the $\bar{p}p$ mass spectrum have also been reported below $\bar{p}p$ threshold, in $J/\psi \to \gamma\bar{p}p$ [88–90] and in $B^+ \to K^+\bar{p}p$, $B^0 \to K_S^0\bar{p}p$ [91,92] and $\bar{B}^0 \to D^0\bar{p}p$ [93]. This enhancement could be due to a 0^{-+} baryonium [94]. Note that such a pole is not necessarily a compact $qqq\bar{q}\bar{q}\bar{q}$ state but might as well be generated via non-perturbative nucleon–antinucleon final state interactions [95–98]. However, also other explanations have been proposed, such as the dynamics of the fragmentation mechanism [92]. Note that also the copious data on $e^+e^- \to n\pi$ [99,100] appear to be largely explained by the same nucleon–antinucleon final state interactions mentioned above [101].

The pronounced signal observed in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ around $\sqrt{s} = 4.63$ GeV by Belle [102] was argued to be a strong evidence in favor of an interpretation of $Y(4660)$ as charmed baryonium [103]. However, this picture was challenged in Ref. 104.

95.1.4. ***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 or 1. The mass spectrum of hybrids with exotic (non-$q\overline{q}$) quantum numbers was predicted in Ref. 105, while Ref. 106 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 [107,108]. Most hybrids are expected to be rather broad, but some can be as narrow as 100 MeV [110]. They prefer to decay into a pair of S- and P-wave mesons. The lattice study in Ref. 23 [109], 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 Ref. 111.

A $J^{PC} = 1^{-+}$ exotic meson, $\pi_1(1400)$, was reported in $\pi^- p \to \eta\pi^- p$ [112,113] and in $\pi^- p \to \eta\pi^0 n$ [114]. 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 has been reported earlier in $\pi^- p$ reactions [115], but ambiguous solutions in the partial wave analysis were pointed out in Ref. 116 [117]. A resonating 1^{-+} contribution to the $\eta\pi$ P-wave is also required in the Dalitz plot analysis of $\overline{p}n$ annihilation into $\pi^-\pi^0\eta$ [118], and in $\overline{p}p$ annihilation into $\pi^0\pi^0\eta$ [119]. Mass and width are consistent with the results of Ref. 112.

Another 1^{-+} state, $\pi_1(1600)$, decaying into $\rho\pi$, was reported by COMPASS with 190 GeV pions hitting a lead target [120]. It was observed earlier in $\pi^- p$ interactions in the decay modes $\eta'\pi$ [121], $f_1(1285)\pi$ [122], and $\omega\pi\pi$ [123], $b_1(1235)\pi$, but not $\eta\pi$ [124]. A strong enhancement in the 1^{-+} $\eta'\pi$ wave, compared to $\eta\pi$, was reported at this mass in [125]. Ref. 126 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 [127]. Finally, evidence for a $\pi_1(2015)$ has also been reported [122,123].

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 [128], while the strong $\eta'\pi$ coupling of the latter is favored for hybrid states [129,130]. The mass of $\pi_1(1600)$ is also not far below the lattice prediction.

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 [120,131], 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 Ref. 132. A candidate for the 2^{-+} hybrid, the $\eta_2(1870)$, was reported in $\gamma\gamma$ interactions [133], in $\overline{p}p$ annihilation [134], and in central production [135]. 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 $f_2(1270)\pi$ [134], with a relative rate compatible with a hybrid state [106].

95.2. Heavy-light systems

Two very narrow states, $D^*_{s0}(2317)^\pm$ and $D_{s1}(2460)^\pm$, were observed at B factories [136,137]. 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 [138–140] or DK (DK^*) molecules [141–145]. 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 occurring 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 $D^*_{s0}(2317)^\pm$ [143–145]. More compact structures typically produce widths below 10 keV [146,147]. Currently there exists an upper bound for the width of 3.8 MeV.

It should be stressed that – akin to $q\overline{q}$ mesons – hadronic molecules also appear in multiplets. Recent studies [148–150] show that, if $D_{s0}(2317)$ were of molecular nature, the lowest non-strange scalar D-state, the $D^*_0(2400)$, would also be molecular in nature, with a two-pole structure similar to the $\Lambda(1405)$ (see the minireview "Pole structure of the $\Lambda(1405)$ region"). In Ref. 149 this assignment is demonstrated to be consistent with recent data from LHCb on $B^- \to D^+\pi^-\pi^-$ [151].

95.3. Heavy-heavy systems

Several unexpected states have been observed in the previous years in both the charmonium and the bottomonium region. With the discovery of the $X(3872)$ in $B^\pm \to K^\pm X$ ($X \to J/\psi\,\pi^+\pi^-$) by Belle [152] in 2003, soon confirmed by BaBar [153], many searches for states beyond the standard quark model were initiated both in the charm and in the bottom sectors. For an updated collection of the currently available experimental information on multiquark states we refer to the mini-review on 'Spectroscopy of mesons containing two heavy quarks' in this *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 [154]. Those are discussed in some depth in the mini-review on 'Pentaquarks' in this *Review*.

When restricting ourselves to confirmed states we are faced with several states that do not seem to fit into the standard quark model. This is clear for the six established charged states ($Z_c(3900)^\pm$, $Z_c(4020)^\pm$, $Z_c(4200)^\pm$ 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 ($X(3872)$, $Y(4260)$, $Y(4360)$, $Y(4660)$) also challenge the standard quark model 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 [155] and then by relaxing this constraint [156]. 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 [157]. Instead, the $X(3940)$ reported by Belle in $e^+e^- \to J/\psi X$, decaying into $D^*\bar{D}$ but not into $D\bar{D}$ [158], and also observed in $B \to K(X \to \omega J/\psi)$ [159] could be the χ'_{c1}. The 2^3P_2 tensor partner (χ'_{c2}) was reported by Belle at 3931 MeV in $\gamma\gamma$ interactions [160].

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 [161] for which strong isospin breaking is predicted [161,162] due to the nearby 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 [163]. A four-quark state $cq\bar{c}\bar{q}'$ is also possible [140] but unlikely, since the charged partner of the $X(3872)$ has not been observed (e.g. in $B^- \to \bar{K}^0 X^-$ nor in $B^0 \to K^+ X^-$, where $X^- \to J/\psi\,\pi^-\pi^0$ [164]) — see also Ref. 165 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 [166], was challenged in [167] which stresses the importance of rescattering, see also [168,169].

A broad structure, $Y(4260)$, decaying into $J/\psi\,\pi^+\pi^-$ was reported by BaBar in initial state radiation $e^+e^- \to \gamma(e^+e^- \to Y(4260))$ [170]. Recently a measurement with significantly improved statistics was reported from BESIII [171]. The Breit-Wigner fit of these data lead to a mass reduction of 40 MeV, but also required a second state at 4320 MeV. However, the $D_1\bar{D}$ molecular model for the $Y(4260)$ [172] is capable to describe the same data with just one single pole [173].

There are no charmonium states with the quantum numbers 1^{--} not expected in this mass region. 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 $\bar{c}c$ [174,175] or a spin-0 [176,177] core. However, provided that the observation of $Y(4260)$ decay into $h_c(1P)\pi\pi$ by BESIII [178] 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 the review on '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 [179]. To circumvent the spin-symmetry argument [180] 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 $Y(4260)$ [181] would explain 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 prominent $D_1\bar{D}$ component of the $Y(4260)$ allowed for the prediction of a copious production of $X(3872)$ in $Y(4260)$ radiative decays [182]. This prediction was confirmed shortly after at BESIII [183]. The $Y(4360)$ as a $D_1\bar{D}^*$ bound state could be the spin partner of the $Y(4260)$ [184,185], but a detailed microscopic calculation is still lacking.

The tetraquark picture explains the observed Y states [186] and, when including a tailor-made spin-spin interaction [187], is also capable to describe the $X(3872)$, both

$Z_c(3900)^{\pm,0}$ and $Z_c(4020)^{\pm}$ and even the recently confirmed $Z(4430)^{\pm}$ by Belle [188]. However, the model predicts many additional charged and neutral states which have not yet been discovered. For a possible explanation of this we refer to Ref. 165.

The charged states $Z_c(3900)^{\pm}$, first observed by BESIII [189] and the $Z_c(4020)^{\pm}$ [190] decay predominantly into $\bar{D}D^*$ and $\bar{D}^*D^*$, respectively, while $Z_b(10610)^{\pm,0}$ and $Z_b(10650)^{\pm}$ [191,192] decay predominantly into $\bar{B}B^*$ and $\bar{B}^*B^*$ [193], respectively, although all of them were discovered in the decay mode heavy quarkonium and pion. This suggests that the 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 [194] and also shortly after that of the $Z_c(3900)^{\pm}$ [181]. However, some of their properties also appear to be consistent with tetraquark structures [195]. If the molecular picture were correct for the Z_b states spin, symmetry allows for the prediction of spin partner states [196] which are still to be found.

The heaviest confirmed charged state in the charmonium sector is the $Z(4430)^{\pm}$ observed by Belle [188]. It is interpreted as hadrocharmonium [179], $\bar{D}_1D^*$ molecule [197] as well as tetraquark state [187]. Alternatively, in Refs. 198,199 the $Z(4430)^{\pm}$ was explained as a cross-channel effect enhanced by a triangle singularity.

It should be stressed that the various scenarios, while describing the data, also make decisive predictions, e.g. yet unobserved quantum numbers [200,186]. The forthcoming data on heavy meson spectroscopy from various facilities should soon provide a much deeper understanding on how QCD forms matter out of quarks and gluons.

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