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Multiquark States

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Abstract

Why do we see certain types of strongly interacting elementary particles and not others? This question was posed over 50 years ago in the context of the quark model. M. Gell-Mann and G. Zweig proposed that the known mesons were $q\bar{q}$ and baryons qqq, with quarks known at the time u ("up"), d ("down"), and s ("strange") having charges (2/3,–1/3,–1/3). Mesons and baryons would then have integral charges. Mesons such as $qq\bar{q}\bar{q}$ and baryons such as $qqqq\bar{q}$ would also have integral charges. Why weren't they seen? They *have* now been seen, but only with additional heavy quarks and under conditions which tell us a lot about the strong interactions and how they manifest themselves. The present article describes recent progress in our understanding of such "exotic" mesons and baryons.

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1 INTRODUCTION

Why do we see certain types of elementary particles and not others? This question was posed over 50 years ago in the context of the quark model [1]. M. Gell-Mann and G. Zweig proposed that the known mesons were $q\bar{q}$ and baryons qqq, with quarks known at the time u ("up"), d ("down"), and s ("strange") having charges (2/3,–1/3,–1/3). Mesons and baryons would then have integral charges. Mesons such as $qq\bar{q}\bar{q}$ and baryons such as $qqqq\bar{q}$ would also have integral charges. Why weren't they seen? They *have* now been seen, but only with additional heavy quarks and under conditions which tell us a lot about the strong interactions and how they manifest themselves. The present article describes recent progress in our understanding of such "exotic" mesons and baryons.

After some introductory words on early multiquark states, the quark model, and quantum chromodynamics (QCD), we discuss light multiquark candidates in Sec. 2, heavy-light multiquark candidates in Sec. 3, and heavy quarkonium-like multiquark candidates in Sec. 4. We treat states beyond those detected at present in Sec. 5, and summarize in Sec. 6.

1.1 Nucleons And Their Molecules

The symmetries of the strong interactions have a long history, starting with isotopic spin (*isospin*) which recognized the similarity of the neutron and proton despite their different charges. An important role in understanding forces which bind multiple neutrons and protons (*nucleons*) into nuclei is played by the *pion*, coupling to nucleons in an isospin-invariant way. With exchange of pions and other heavier mesons, it was possible to understand the masses of nuclei, with the deuteron (a neutron-proton bound state) a case in point. To the degree that nucleons in nuclei retain much of their identity, one may think of nuclei as the first "molecules" of elementary particles.

1.2 Quark Model

Starting in the late 1940s, initially in cosmic rays but by 1953 also in particle accelerators, a new degree of freedom, known as *strangeness*, began to be recognized in mesons and baryons [2]. Mesons and baryons could be classified into isospin multiplets with their charges Q, the third component I_3 of their isospin I, and their *hypercharge* Y (a quantum number conserved in their strong production) related by $Q = I_3 + Y/2$. (The hypercharge is related to a quantum number S, for "strangeness," by $Y = S + B$, where B is baryon number.) However, in the 1950s it was not yet understood why certain isospin multiplets appeared and not others, and how the observed ones were related to one another.

By the early 1960s, it became clear that low-lying baryons included the nucleon isospin doublet (n, p) with $Y = 1$, an isospin singlet Λ and an isospin triplet $\Sigma^-, \Sigma^0, \Sigma^+$ with $Y = 0$, and an isospin doublet Ξ^-, Ξ^0 with $Y = -1$. These could be unified into an eight-dimensional representation of the symmetry group SU(3) [3]. The lowest-lying mesons, including the pion and charged and neutral *kaons*, also could be fit into an eight-fold multiplet along with a predicted meson called the η, soon discovered [4].

Given the spin $J = 1/2$ and parity $P = +$ of the neutron and proton, their partners in the SU(3) octet were predicted (and eventually observed) to have $J^P = 1/2^+$. But by the early 1960s a multiplet of resonant particles with $J^P = 3/2^+$ was also taking shape: an isoquartet $\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$ with $Y = 1$, a heavier isotriplet $\Sigma^{*-}, \Sigma^{*0}, \Sigma^{*+}$ with $Y = 0$, and a still heavier isodoublet Ξ^{*-}, Ξ^{*0} with $Y = -1$. The SU(3) scheme predicted that these were members of a ten-dimensional representation, to be completed by a predicted isosinglet Ω^-. It also predicted an equal-spacing rule $M(\Omega) - M(\Xi^*) = M(\Xi^*) - M(\Sigma^*) = M(\Sigma^*) - M(\Delta)$. The second equality was known to hold, and the predicted Ω was discovered in 1964, cementing confidence in SU(3) [5].

The quark model [1] (see also [6]) provided an explanation of SU(3), with the quarks forming a fundamental triplet out of which all SU(3) representations could be built. For example, the ten-dimensional baryon representation containing four Δ, three Σ^*, two Ξ^*,

and one Ω could be regarded as the totally symmetric qqq combinations of u, d, and s. The dynamics of quarks featured prominently at the 1966 International Conference on High energy Physics in Berkeley. It seemed possible to describe several hundred resonant particles in terms of three quarks for baryons and a quark-antiquark pair for mesons.

A nagging question dealt with quark statistics. The Δ^{++} was seen as a ground state of three u quarks with a total $J = 3/2$, implying total symmetry in its space $\times$ spin wave function. But as a state of fermions, its total wave function should be *antisymmetric*. The invention of another degree of freedom [7], now called *color*, in which every qqq state could be totally antisymmetric, solved this problem, and provided a basis for the interaction of quarks with one another through the exchange of *gluons*. This picture came to be known as *quantum chromodynamics*, or QCD.

QCD also explained why quarks could form only integrally-charged states, with their fractional charges masked by binding to other pairs of quarks or antiquarks. However, the question remained, to this day, why other integrally-charged states such as $qq\bar{q}\bar{q}$ or $qqqq\bar{q}$, were not observed.

Significant evidence for the reality of quarks came from deep inelastic scattering of electrons on protons at the Stanford Linear Accelerator Center [8], recoiling against pointlike objects consistent with quarks. That these objects indeed appeared to have fractional charge was indicated by a comparison of deep inelastic electron scattering with that of neutrinos (see, e.g., [9]).

The light quarks u, d, s were eventually joined by heavier ones: c ("charm") [10], b ("beauty" or "bottom") [11], and t ("top") [12]. In contrast to the light quarks, whose properties and effective masses inside mesons and baryons were strongly affected by the QCD interaction, c and b are amenable to approximately nonrelativistic descriptions, as their masses (~ 1.5 and 5 GeV, respectively) exceed their typical kinetic energies (a few hundred MeV) inside mesons and baryons. (Top quarks form only a fleeting association with other quarks before they decay weakly, having a mass of more than twice that of the W boson.)

1.3 Quantum Chromodynamics

The theory of the strong interactions, QCD, was born in a mathematical investigation by Yang and Mills [13] of isotopic spin as a *gauge theory*. In contrast to electrodynamics, the quanta of a gauged isospin theory carry charges. One consequence of this is a different scale dependence of the interaction strength. The electrodynamic force becomes stronger at short distances (large momentum-transfer scales), while in a Yang-Mills type of theory the force becomes weaker at short distances ("asymptotic freedom"). The relevant calculation, not then understood as signaling asymptotic freedom, first appeared in a theory based on gauged SU(2) symmetry [14]. Asymptotic freedom was noticed by 't Hooft in 1972 but never published [15]; and calculated in all generality for Yang-Mills (*non-Abelian gauge*) theories by Gross and Wilczek [16] and Politzer [17].

A gauged SU(3) as the theory of the strong interactions contains the "color" ingredient necessary to understand why the ground states of baryons have quark wave functions that are *symmetric* in space $\times$ spin $\times$ *flavor*, where the last term denotes the quark label $u, d, s, \ldots$. Each quark comes in one of three colors, and a wave function totally

antisymmetric in color can be constructed by taking one of each color.

The behavior of the strong interaction at *long* distances is also different from that of the electromagnetic interaction. The gluons, quanta of the strong interactions, interact with one another in such a way that lines of force between a quark and an antiquark bunch up into a tube of essentially constant cross-section area, leading by Gauss' Law to a constant force at large distances, or a linearly rising potential. (For recent comments on this picture see Refs. [18] and references therein.) When this potential becomes strong enough, a new quark-antiquark pair is created, shielding the color charges of the original pair. Thus quark confinement is an essential consequence of QCD.

The strengthening of the QCD coupling at low momentum scales and large distance scales means that perturbation theory is unsuitable in that regime. The leading method for dealing with this behavior is to put spacetime onto a *lattice*. The limit as the lattice spacing a tends to zero then may be taken. However, the presence of pions, with a very long Compton wavelength, means that the total spatial extent of the lattice has to be large. Coupled with the need to take $a \to 0$, this leads to the requirement of very large lattices, and typically fictional pions which are somewhat heavier than the real ones.

The time-dependence of a spatial-lattice state can be described by taking Euclidean time, whereby a dependence e^{-imt} in Minkowski space is converted to $e^{-m\tau}$, where $\tau \equiv it$. In the limit $\tau \to \infty$, a matrix element will behave as $e^{-m_0\tau}$, where m_0 is the mass of the lightest contributing intermediate state. Subtracting off this contribution, one can obtain, with some sacrifice in accuracy, the contribution of the next-lowest intermediate state, and this process can be repeated until statistical limitations set in.

Lattice QCD has been very successful in reproducing the masses of known states involving u, d, s, c, b quarks. It has also been the leading means for calculating *form factors* and *pseudoscalar meson decay constants*, which are more sensitive to wave function details. This is particularly so now that virtual light-quark-antiquark pairs have been taken into account in the *unquenched* approximation. The most sophisticated calculations even consider virtual $c\bar{c}$ pairs when calculating properties of states containing b quarks. Remaining possible sources of uncertainty include the need for proper treatment of chiral fermions and the use of chiral perturbation theory for extrapolation of calculations involving pions down to their physical mass.

1.4 QCD Motivated Models

1.4.1 Potential Models

The discoveries of the charmed and beauty quarks, and their rich $c\bar{c}$ and $b\bar{b}$ spectra, led to approximate descriptions of their spectra by nonrelativistic potential models [19, 20], including those with relativistic corrections [21]. The short-distance behavior of the interquark potential could be described by a Coulomb-like potential, suitably modified by a logarithmic correction due to asymptotic freedom, while the long-distance behavior was linear in the separation r (see the above description of quark confinement). An interpolation between these two behaviors was provided by a potential logarithmic in r [22], for which the spacing between $Q\bar{Q}$ levels was independent of the mass m_Q of the quark Q, as is nearly the case for $c\bar{c}$ and $b\bar{b}$ systems.

Treating light quarks in bound states as having effective masses of several hundred MeV, and taking into account spin-spin (hyperfine) interactions among them, it was even found possible to bypass many details of potential models, gaining an insight into masses of light mesons and baryons or those containing no more than one heavy quark (c or b). This approach was pioneered in Ref. [23] and applied, for example, to baryons containing b quarks in Refs. [24].

1.4.2 Diquarks

A baryon is made of three color-triplet quarks, coupled up to a color singlet using the antisymmetric tensor $\epsilon_{\alpha\beta\gamma}$, where the indices range from 1 to 3. Each quark pair must then act as a color antitriplet. Under some circumstances it is then useful to consider a baryon as a bound state of a color triplet quark and a color-antisymmetric antitriplet *diquark*. The color antisymmetry of the diquark requires its space $\times$ spin $\times$ flavor wave function to be *symmetric*, where *flavor* denotes quark identity ($u, d, s, \ldots$). For example, the u and d quarks in the isosinglet baryon Λ are in an S wave (space symmetric) and an isospin zero state (flavor antisymmetric), so they must be in a spin zero state (spin antisymmetric). The spin of the Λ is then carried entirely by the strange quark, consistent with its measured magnetic moment [25].

Some light-quark resonances have been identified as candidates for diquark-antidiquark bound states [26, 27], with the last noting a relation to baryon-antibaryon resonances [28] reminiscent of the original Fermi-Yang model of the pion [29] as a nucleon-antinucleon bound state. The past light-quark pentaquark candidates brought attention to a role diquarks can play in formation of such systems [30]. Even though these candidates did not survive experimental scrutiny (see Sec 2.2), the discussion on the role of diquarks in shaping the structure of ordinary and exotic baryons [31] is very much alive today.

1.4.3 Tightly Bound Multiquark States

In addition to the above light-quark resonances, some authors have postulated that new resonances including one or more heavy quarks are candidates for tightly bound diquark-antidiquark states [32, 33, 34]. Thus, the $X(3872)$ first observed decaying to $J/\psi\pi^+\pi^-$ [35] would be interpreted as a bound state of a cu diquark and a $\bar{c}\bar{u}$ antidiquark. We shall discuss the merits and drawbacks of this assignment presently.

1.4.4 Hadrocharmonium

The resonance $X(3872)$ mentioned above can be regarded as a charmonium state embedded in light hadronic matter, called *hadrocharmonium* in Ref. [36]. This classification is motivated by the observation that multiquark states including a $c\bar{c}$ pair appear to contain only a single charmonium state, whereas one might expect the wave function to involve a linear combination of several charmonium states in a hadronic molecule or generic multiquark state.

1.4.5 Molecular States

The wave functions of many exotic multiquark states such as $X(3872)$ appear to consist, at least in part, of pairs of hadrons each containing one heavy quark. Thus, one can identify $X(3872)$ as a bound or nearly bound state of $(D^0 = c\bar{u})(\bar{D}^{*0} = \bar{c}u)$ + (charge conjugate), as we shall discuss in Sec. 4. Such assignments are favored if the constituents can be bound via exchange of a light pseudoscalar, such as pion [37, 38, 39] or possibly η [40]. As in the case of the deuteron, pion exchange is not the whole story, but, where permitted, dominates the long-range force.

1.4.6 Cusps and Anomalous Triangle Singularities

When a decay process involves three particles in the final state, the proximity of S-wave thresholds in two-body rescattering can lead to behavior which can mimic a resonance while only consisting of a cusp. Kinematic enhancements can also be due to *anomalous triangle singularities* (for an early manifestation in pion-nucleon scattering see [41]), in which resonance-like behavior is seen when all participants in rescattering approach the mass shell. Triangle singularities and methods to identify true resonances as S-matrix poles have been recently discussed in Refs. [42, 43, 44].

2 LIGHT MULTIQUARK CANDIDATES

2.1 Light Meson Multiquark Candidates

The P-wave $q\bar{q}$ states of the three light quarks $q = u, d, s$ consist of ${}^3P_{0,1,2}$ and ${}^1P_1$ nonets with positive parity. Here the superscript denotes the quark-spin multiplicity $2S_q + 1$, while the subscript denotes the total spin J. The $J = 0$ states can couple to a pair of pseudoscalar mesons in an S wave, and hence their widths and masses are strongly influenced by these couplings. Indeed, one can regard them as linear combinations of $q\bar{q}$ and meson-meson states. The latter can be thought of as $qq\bar{q}\bar{q}$, or *tetraquarks*. A systematic classification of light $J = 0$ mesons as tetraquarks was made by Jaffe [26, 27].

The two-pseudoscalar-meson channel strongly affects the production and decay of the nonstrange $J = 0$ mesons $f_0(980)$ (isoscalar) and $a_0(980)$ (isovector) [25]. They lie very close to the $K\bar{K}$ threshold and thus may be thought of, in part, as either $K\bar{K}$ bound states or tetraquarks containing an $s\bar{s}$ pair. The f_0 is seen to decay predominantly to $\pi\pi$, but is produced primarily in processes which provide an initial $s\bar{s}$ pair, such as $B_s^0 \to J/\psi\ f_0$ [45].

Another light-quark system in which meson, rather than quark, degrees of freedom play an important role is the f_1 or a_1 system decaying to $K\bar{K}\pi$ with mass around 1420 MeV. The Dalitz plot near this total mass shows a_0 or f_0, K^*,$\bar{K}^0$ resonances between each final-state pair [46]. The $f_1(1420)$ thus may not be a genuine resonance but rather a kinematic effect known as a *triangle singularity* [47].

Cusp-like behavior in scattering amplitudes near S-wave thresholds for new final states is widespread [48]. For one example, diffractive photoproduction of $3\pi^+3\pi^-$ exhibits a

dip near $p\bar{p}$ threshold [49]. There may also be a $p\bar{p}$ resonance or bound state near this mass, but the question is not settled [48].

2.2 Light Baryon Multiquark Candidates

The quark model for baryons has been very successful in describing them as qqq states, including those with nonzero internal orbital angular momentum. However, final meson-baryon states (and thus states of $q\bar{q}+qqq$) play an important role as well. A case in point is the resonance known as $\Lambda(1405)$, with $J^P = 1/2^-$. It has a history going as far back as the late 1950s [50]; for a recent understanding of its structure see Ref. [51]. Its nature is still being debated, though it is a reasonable candidate for a $\bar{K}N$ bound state. The quark model predicts three $J^P = 1/2^-$ isospin-zero baryons: a flavor singlet with quark spin 1/2 and two flavor octets, one with quark spin 1/2 and the other with quark spin 3/2. The $\Lambda(1405)$ appears to be mainly the flavor singlet, with smaller admixtures of the two octets [52]. Two other states, $\Lambda(1670, 1/2^-)$ and $\Lambda(1800, 1/2^-)$ [25], are the orthogonal mixtures. Couplings to the channels $\Sigma\pi$, $N\bar{K}$, and $\Lambda\eta$ probably play some role in the mixing [53].

A candidate for a K^+n resonance called $\Theta^+(1540)$, whose minimal quark content would be $\bar{s}uudd$, was observed in the early 2000s [54]. However, it was not confirmed in further experiments [55] and appears to have been a kinematic effect [56].

3 HEAVY-LIGHT MULTIQUARK CANDIDATES

3.1 Heavy-Light Meson Multiquark Candidates

The S-wave states of a charmed quark and a light (u, d, s) antiquark are the pseudoscalar mesons D^0, D^+, and D_s^+ ($^1S_0$) and the vector mesons D^{*0}, D^{*+}, and D_s^{*+} ($^3S_1$). The P-wave states naturally divide into those with light-quark total angular momentum $j = 1/2$ ($J_j^P = 0_{1/2}^+,\ 1_{1/2}^+$) and $j = 3/2$ ($J_j^P = 1_{3/2}^+, 2_{3/2}^+$) [57]. They are predicted to decay to ground-state charmed mesons in the following ways, where P stands for π or K: $0_{1/2}^+ \to DP\ (L = 0)$; $1_{1/2}^+ \to D^*P\ (L = 0)$; $1_{3/2}^+ \to D^*P\ (L = 2)$; $2_{3/2}^+ \to (D, D^*)P\ (L = 2)$. The states with $j = 3/2$ decaying via D-waves are expected to be narrow, and indeed correspond to the observed $D_1(2420)$, $D_2(2460)$, $D_{s1}(2536)$, and $D_{s2}(2573)$ [25]. (Here the subscript denotes total J.) Information is fragmentary on the nonstrange $j = 1/2$ states but there exists a broad candidate for the nonstrange $0_{1/2}^+$ state with mass $M = 2318 \pm 29$ MeV and width $\Gamma = 267 \pm 40$ MeV [25]. When both strange and nonstrange candidates for the same (J, j) are seen, the strange candidate is about 115 MeV heavier than the nonstrange candidate. Thus we would expect a strange $0_{1/2}^+$ state around $115 + 2318 = 2433$ MeV, above the DK threshold of 2362 MeV.

What came as a surprise was the observation by the BaBar Collaboration [58] of a candidate for the strange $0_{1/2}^+$ state at 2317 MeV, more than 100 MeV below naïve expectations and 45 MeV below DK threshold. It was seen instead to decay to $D_s\pi^0$ via an isospin-violating transition. A hint of a strange state at 2460 MeV, decaying to $D_s\pi^0\gamma$,

was also seen. Its confirmation [59, 60, 61] supplied a candidate for the strange $1^+_{1/2}$ state [62, 63], 40 MeV below D^*K threshold.

Proposals for explaining the displacement of $D_{s0}(2317)$ and $D_{s1}(2460)$ masses from their expected values included the formation of $D^{(*)}K$ molecules or bound states [64], the existence of tetraquarks [65, 66, 67, 68], and a realization of chiral symmetry which predicted the observed mass pattern a number of years earlier [69, 70, 71, 72]. The yet-to-be-detected conjectured bottom analogues of $D_{s0}(2317)$ $D_{s1}(2460)$ are discussed in Sec. 5.

3.2 Heavy-Light Baryon Multiquark Candidates

Threshold effects can involve heavy mesons and light-quark baryons, or heavy baryons and light-quark mesons. An example of the former is a charmed baryon resonance $\Lambda_c(2940)$, seen decaying to D^0p [73]. The mass was seen to be just below $D^{*0}p$ threshold, suggesting a bound state or molecular interpretation [74, 75]. Recently the LHCb Collaboration [76] has analyzed the D^0p amplitude in $\Lambda_b \to D^0p\pi^-$ and finds a resonance favoring $J^P = 3/2^-$ at a mass of $2944.8^{+3.5}_{-2.5} \pm 0.4^{+0.1}_{-4.6}$ MeV with a width of $27.7^{+8.0}_{-6.8} \pm 0.8^{+5.2}_{-10.4}$ MeV. The J^P assignment is consistent with an S-wave state of a D^{*0} and a proton.

Following the alleged discovery of the $\Theta(1540)$ pentaquark candidate (see Sec. 2.2) a $\bar{c}uudd$ state was claimed by the H1 Collaboration at HERA in Hamburg [77], corresponding to an effective mass of 3.1 GeV in the $D^{*\pm}p^{\mp}$ system. It was not confirmed with further data [78].

4 HEAVY QUARKONIUM-LIKE MULTIQUARK CANDIDATES

4.1 Ground rules

In this section we shall discuss states containing two heavy quarks Q which cannot be represented as simple $Q\bar{Q}$ excitations, but which require some admixture of light quarks as well. The notation X will stand for neutral "cryptoexotic" states with likely $Q\bar{Q}q\bar{q}$ content. States in this category with $J^{PC} = 1^{--}$ which can couple directly to a virtual photon will be denoted Y, while those with a charged light-quark pair (e.g., $u\bar{d}$) will be denoted Z_c (when the heavy pair is $c\bar{c}$) or Z_b (when the heavy pair is $b\bar{b}$). Finally, P_c or P_b will denote a state such as $c\bar{c}uud$ or $b\bar{b}uud$ ("pentaquark").

The spectrum of X, Y, Z states is particularly rich for charmonium. Some controversy exists over the quark content, spin, and parity of many of these states. A useful reference to the experimental literature is contained in Ref. [79]. We shall not discuss in any detail states which we believe to have conventional $Q\bar{Q}$ assignments, concentrating instead on X, Y, Z, and P_Q candidates.

4.2 The $X(3872)$ State

The first evidence for a multiquark state involving $c\bar{c}$ and light quarks came from the decay $B \to K\pi^+\pi^- J/\psi$, in which the $\pi^+\pi^- J/\psi$ system showed a narrow peak around 3872 MeV [35]. It has been confirmed by many other experiments [25], as illustrated in Fig. 1. Its width is less than 1.2 MeV, and its J^{PC} has been established as 1^{++} [80].

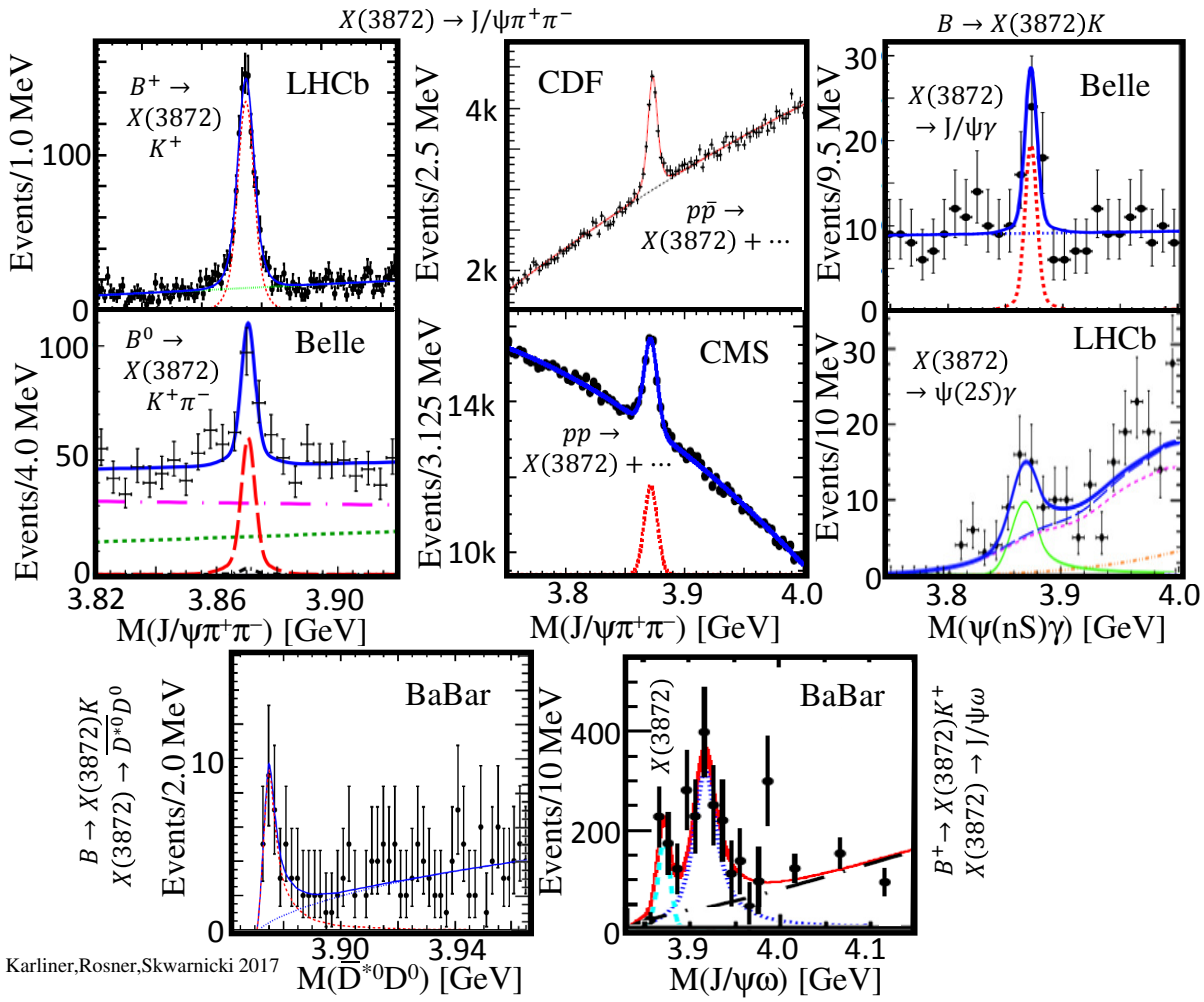

Figure 1: Production and decay of the $X(3872)$ state. Detailed figure descriptions can be found in the original references, from which the plots have been adapted: **top row** left Ref. [80], middle Ref. [81], right [82], **middle row** left Ref. [83], middle Ref. [84], right Ref. [85], **bottom row** left Ref. [86], and right Ref. [87].

The mass of $X(3872)$, whose 2016 average [25] is 3871.69 ± 0.17 MeV, is sufficiently close to the threshold for $D^0\bar{D}^{*0}$, namely $(1864.83 \pm 0.05) + (2006.85 \pm 0.05) = (3871.68 \pm 0.07)$ MeV, that one cannot tell whether it is a candidate for a bound state or resonance

of $D^0\bar{D}^{*0}$. Clearly, however, the neutral-D channel must play an important role in the makeup of $X(3872)$, as also evidenced by a large fall-apart rate of the $X(3872)$ to $D^0\bar{D}^{*0}$, once the kinematic threshold is exceeded [88, 86, 89] (Fig. 1). The D^+D^{*-} threshold, $(1869.59 \pm 0.09) + (2010.26 \pm 0.05) = (3879.85 \pm 0.10)$ MeV, is sufficiently far from $M(X(3872))$ that the charged-D channel appears to play a much less important role in its composition.

The quark makeup of $X(3872)$ thus should include an important $c\bar{c}u\bar{u}$ component. Confirmation of this point is provided by the observation of both $X(3872) \to \omega J/\psi$ ($\omega \to \pi^+\pi^-\pi^0$) [90, 87] and $X(3872) \to \rho^0 J/\psi$ ($\rho^0 \to \pi^+\pi^-$) [91, 80], implying that the $X(3872)$ is a mixture of isospins zero and one [38] (Fig. 1). There also appears to be a $c\bar{c}$ $\chi_{c1}(2P)$ component to the $X(3872)$ wave function, as indicated by the ratio of the radiative decays to $\gamma J/\psi$ and $\gamma\psi(2S)$ [85] (Fig. 1),

$$R_\gamma \equiv \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 2.46 \pm 0.64 \pm 0.29\,. \tag{1}$$

The measured value is consistent with pure charmonium and a mixture of charmonium and a molecular state, but not with a pure molecular state. Additional rather robust evidence for the $\bar{c}c$ component is provided by the relatively large cross section for prompt production of $X(3872)$ in $p\bar{p}$ [92, 93] and pp collisions [94, 84, 95] (Fig. 1), closely following behavior of the $\psi(2S)$ state.

In particular, Ref. [96] uses ALICE data on the production of light nuclei with $p_T \lesssim 10$ GeV in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV to estimate the expected production cross sections of such nuclei in pp collisions at high p_T. Hypertriton, helium-3, and deuteron production cross sections are compared to the CMS results for prompt production of $X(3872)$ [84]. Fig. 1 of Ref. [96] shows that the latter is orders of magnitude larger than the former. Also the dependence of the prompt production of $X(3872)$ on its transverse momentum and pseudo-rapidity, as well as the ratio of the prompt production to the production in B meson decays, closely follow those of the $\psi(2S)$ charmonium state, pointing to the same production mechanism [93, 95].

The cross section for prompt production of these light nuclei falls rapidly with p_T because they are rather large. As soon as p_T is bigger than their inverse radius, the probability of forming such weakly bound molecular states becomes very small. The $X(3872)$ binding energy is much smaller than the 2.2 MeV deuteron binding energy. Therefore the spatial extent of the molecular component must be much bigger than the already large deuteron size.

We can estimate the inverse size of the $X(3872)$ molecular component using the formula

$$1/r = \sqrt{2\mu|\Delta E|} \tag{2}$$

where $\mu = 967$ MeV is the reduced mass and ΔE is the binding energy. ΔE is at most 0.2 MeV, probably less. This gives $1/r \lesssim 20$ MeV, corresponding to radius of $\gtrsim 10$ fermi, really huge. With such a large radius the cross section for production of the molecular component at $p_T \gtrsim 10$ GeV is expected to be negligible. Therefore $X(3872)$ must have a significant $c\bar{c}$ component, whose size is the typical hadronic radius < 1 fermi, much

smaller than the size of the molecular component.[1]

This of course raises the interesting question of how the mixing works for two states whose sizes differ by at least a factor of 10. Perhaps $X(3872)$ lives long enough to make even a small spatial overlap sufficient for significant mixing.[2] It is also possible that the molecular component occurs dynamically when the compact $X(3872)$ attempts to disintegrate to $D^0\bar{D}^{*0}$.

Hadronic molecules were proposed some time ago [37, 99, 100, 101]. One-pion exchange plays an important (though not exclusive) role in facilitating binding. The attractive force between two states of isospin $I_{1,2}$ and spin $S_{1,2}$ transforms as

$$V \sim \pm I_1 \cdot I_2 \; S_1 \cdot S_2 \quad \text{for } (qq,\ q\bar{q}) \text{ interactions}, \tag{3}$$

and is expected to bind not only $D^0\bar{D}^{*0} + \text{c.c.}$ but many other systems as well, including meson-meson, meson-baryon and baryon-baryon [39]. In particular, there should be an analogue X_b of the $X(3872)$, near $B\bar{B}^*$ threshold (10604.8 ± 0.4 MeV for neutral B-s and 10604.5 ± 0.4 MeV for B^+B^{-*}) [102]. Because the thresholds for charged and neutral pairs are so similar, isospin impurity in the X_b is expected to be small, and it should be mostly isoscalar.

CMS and ATLAS have searched for the decay $X_b \to \Upsilon(1S)\pi^+\pi^-$ [103]. The search in this particular channel was motivated by the seemingly analogous decay $X(3872) \to J/\psi\,\pi^+\pi^-$. This analogy is misguided, however, because for an isoscalar with $J^{PC} = 1^{++}$ such a decay is forbidden by G-parity conservation [104]. Thus the null result of these searches does not tell us anything about the existence of X_b.

The bottomonium state $\chi_{b1}(3P)$ has been recently observed [105]. The X_b state could mix with it and share its decay channels, just as $X(3872)$ is likely a mixture of a $\bar{D}D^*$ molecule and $\chi_{c1}(2P)$ [102]. However, the mass difference between the observed $\chi_{b1}(3P)$ state and $B\bar{B}^*$ thresholds is about 93 MeV, which makes a significant mixing unlikely. In fact, the observed $\chi_{b1}(3P)$ mass is in excellent agreement with the potential model predictions made over 20 years before its first observation [106], while mixing would have likely affected its mass.

4.3 Other Near-threshold Quarkonium-like Mesons

The cross sections for $e^+e^- \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-$ and $e^+e^- \to \Upsilon(1S)K^+K^-$ were found to be surprisingly large near the peak of the $\Upsilon(5S)$ resonance at $\sqrt{s} \sim 10.87$ GeV [107]. One possible explanation of this enhancement was the existence of intermediate $b\bar{b}q_1\bar{q}_2$ states (q_i denotes a light quark) decaying to $\Upsilon(nS)\pi$ or $\Upsilon(1S)K$ [108]. Unusual enhancements were also seen in the cross sections for $e^+e^- \to h_b(nP)\pi^+\pi^-$ ($n = 1, 2$), where $h_b(nP)$ denotes a spin-singlet $b\bar{b}$ resonance with radial quantum number n, orbital angular momentum $L = 1$, and total spin $J = 1$ [109]. These effects were found to be due to two

[1] It was argued that the short-range structure of the molecular wave function is difficult to predict [97, 98], so large values of R_γ and of prompt production cross-section are not incompatible with the molecular behavior of the wave function at large distances. This, however, does not imply that these experimental observations are natural expectations in the molecular model. We side with the argument that an admixture of charmonium 2^3P_1 state offers the most natural explanation, and in fact, is not incompatible with the molecular behavior of $X(3872)$ at large distances.

[2] Alex Bondar, private communication.

charged bottomonium-like resonances in $\Upsilon(5S)$ decays [110]. The $\Upsilon(nS)\pi$ $(n = 1, 2, 3)$ spectra are shown in Fig. 2. The peaks have been named $Z_b(10610)$ and $Z_b(10650)$. Similar peaks are seen in $M(h_b(nP)\pi^+\pi^-)$ $(n = 1, 2)$. The review of Ref. [79] quotes the average masses as $M(Z_b(10610)) = 10607.2 \pm 2.0$ MeV and $M(Z_b(10650) = 10652.2 \pm 1.5$ MeV.

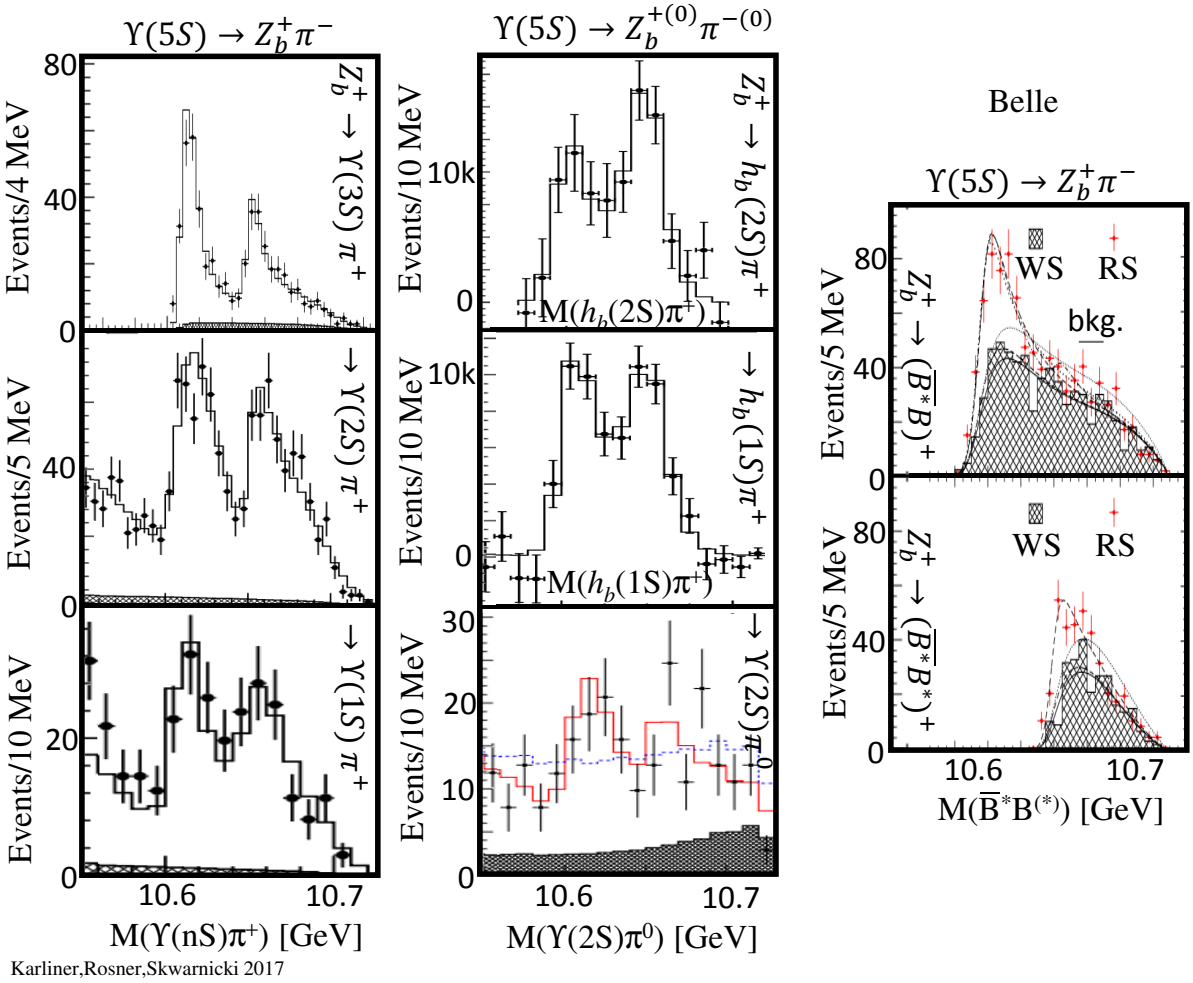

Figure 2: Observations of the $Z_b(10610)$ and $Z_b(10650)$ states. Detailed figure descriptions can be found in the original references, from which the plots have been adapted: **left column** Ref. [110], **middle column** top and middle Ref. [110], bottom Ref. [111], and **right column** Ref. [112].

The masses of the two peaks are very close to the thresholds for $B\bar{B}^*$ and $B^*\bar{B}^*$: (10604.0 ± 0.3) MeV and $(10649.3 \pm 0.5$ MeV, respectively. This suggests that their wave functions should largely consist of the respective S-wave "molecular" components $B\bar{B}^*$ and $B^*\bar{B}^*$ [113]. In fact, the $Z_b(10610)$ fall-apart rate to $B\bar{B}^*$ is large, while there is no

evidence for $Z_b(10650) \to B\bar{B}^*$, which prefers to decay to $B^*\bar{B}^*$ in spite of the smaller phase-space [112] (Fig. 2). The absence of similar effects just above the $B\bar{B}$ threshold of (10558.6 ± 0.3) MeV points to an important role of one-pion exchange in the formation of these "molecules", as a pion cannot couple to the pair of pseudoscalar mesons $B\bar{B}$ [39].

A counterpart to the Z_b system has been observed in exotic charmonium states. The thresholds for [neutral, charged] $D\bar{D}^*$ pairs are $[(3871.7 \pm 0.1),\ (3879.8 \pm 0.1)]$ MeV, while the thresholds for [neutral, charged] $D^*\bar{D}^*$ pairs are $[(4013.7 \pm 0.1),\ (4020.52 \pm 0.1)]$ MeV. States near both these thresholds, respectively called $Z_c(3900)$ and $Z_c(4020)$, have been observed in decays of the vector meson candidate $Y(4260)$ (see next section). The $Z_c(3900)$ is seen in the $\pi\pi J/\psi$ final state as a peak in $M(\pi J/\psi)$ [114, 115, 116, 117] and in the $\pi D\bar{D}^*$ final state as a peak in $M(D\bar{D}^*$ [118, 119], as illustrated in Fig. 3. Its averaged mass is quoted as (3891.2 ± 3.3) MeV [79]. The $Z_c(4020)$ is seen in the $\pi\pi h_c$ final state as a peak in $M(\pi h_c)$ [120, 121] and in the $\pi D^*\bar{D}^*$ final state as a peak in $M(D^*\bar{D}^*)$ [122, 123] (Fig. 3). Its averaged mass is quoted as (4022.9 ± 2.8) MeV [79]. As in the case of the exotic bottomonium Z_c states, the absence of $D\bar{D}$ peaks is circumstantial evidence in favor of a role for pion exchange in forming molecules of open-flavor pairs. As mentioned earlier, such molecules were anticipated shortly after the discovery of charm [99].

As mentioned in Sec. 1.4, many explanations of these near-threshold Z_b and Z_c states abound. The close correlation between peaks and thresholds would have to be regarded as a coincidence in potential models. The grouping of multiple quarks in an exotic hadron depends to some extent on their masses; an example is the predominance of QQ color antitriplet diquarks in $QQ\bar{q}_1\bar{q}_2$ hadrons due to the tight binding of the heavy quarks Q with one another. Explanations based on genuine tetraquarks require the observation of isospin partners; the $Z_c(3900)$ may be the charged partner of $X(3872)$, though this interpretation is complicated by the isospin impurity of the latter. Many of the vector states to be described in the next section may admit of a hadrocharmonium explanation [36]. Finally, experience with light-quark systems such as $f_0(980)$ and $\Lambda(1405)$ indicates that resonant vs. cusp behavior may be difficult to sort out when new channels are opening up. Experience with Feshbach resonances [124], also associated with the opening of new channels, may be of help here.

4.4 Anomalous Vector States

The direct coupling of quarkonium states with $J^{PC} = 1^{--}$ to virtual photons has made them particularly easy to observe. The charm and bottom quarks were first observed as a result of these couplings in the (S-wave) 1^3S_1 states $J/\psi(1S) = c\bar{c}$ and $\Upsilon(1S) = b\bar{b}$, respectively. Weaker couplings to virtual photons also are possessed by the (D-wave) 1^3D_1 states. Here we use the notation $n^{2S+1}L_J$, where n is the radial quantum number, S denotes quark spin, L is represented by $S, P, D, F, \ldots$ for $L = 0, 1, 2, 3, \ldots$, and J denotes total spin of the state. Candidates for such "conventional" vector quarkonia include the following, where we use the name assigned in Ref. [25] and give the approximate mass in MeV:
Charmonium: $J/\psi(1S)(3097), \psi(2S)(3686), \psi(1D)(3770), \psi(3S)(4040), \psi(2D)(4160)$, $\psi(4S)(4415)$;
Bottomonium: $\Upsilon(1S)(9460), \Upsilon(2S)(10023), \Upsilon(3S)(10355), \Upsilon(4S)(10579), \Upsilon(5S)(10860)$,

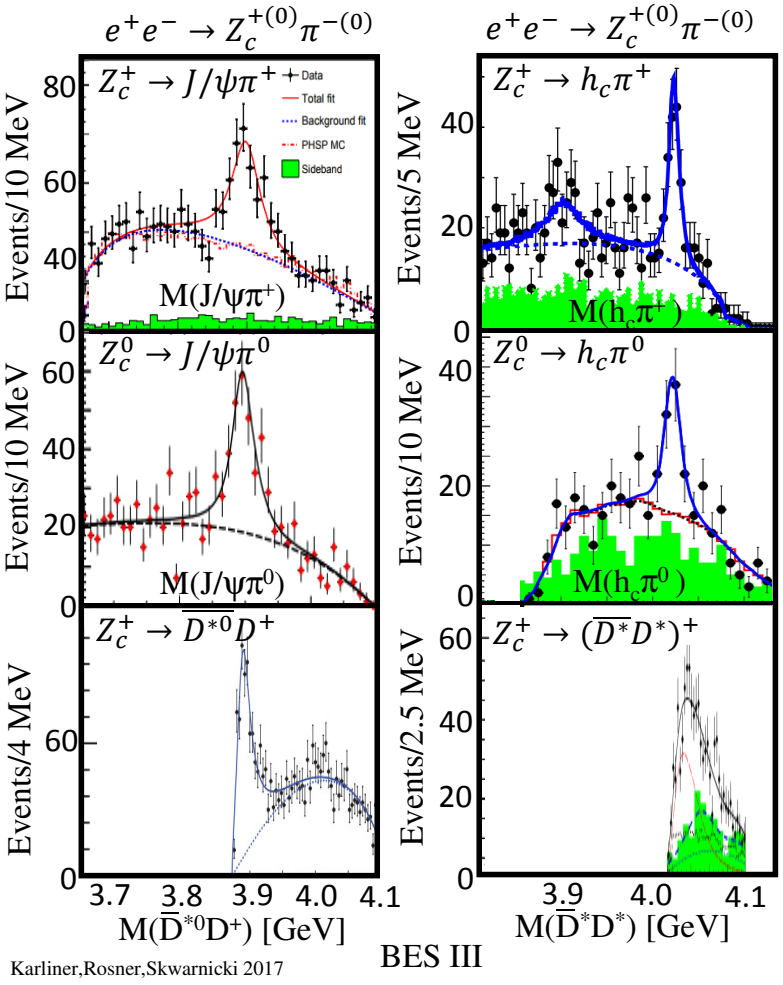

Figure 3: Observations of the $Z_c(3900)$ and $Z_c(4020)$ states. Detailed figure descriptions can be found in the original references, from which the plots have been adapted: **left column** top Ref. [114], middle Ref. [117], bottom Ref. [119], **right column** top Ref. [120], middle Ref. [121], and bottom Ref. [122].

$\Upsilon(6S)(11020)$.

The ratio $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ as measured by BESIII [125] (Fig. 4) peaks prominently around 4040 MeV, and noticeably just above 4400 MeV, motivating the charmonium 3S and 4S assignments for these peaks. A peak associated with the 2D candidate is less prominent, as befits a D-wave state whose coupling to a virtual photon is suppressed. A prominent feature of R is a steep drop around $E_{\text{c.m.}} = 4.2$ GeV. The change in R is more than one unit, which could signify the total suppression of charm production ($\Delta R = -4/3$). Such a sharp dip is often associated with the opening of a new S-wave channel [48], as in the case of $I = 0$ $\pi\pi$ scattering near $K\bar{K}$ threshold. Indeed, the lowest-lying two-body S-wave state into which a $c\bar{c}$ pair can fragment is $D\bar{D}_1 -$ c.c. [126], where D_1 is a P-wave bound state of a charmed quark and a light ($\bar{u}$ or $\bar{d}$) antiquark with $J^P = 1^+$. The minus sign corresponds to the negative C eigenvalue. The lightest established candidate for D_1 has a mass of about 2.42 GeV/c^2, corresponding to a threshold of 4.285 GeV.

The cross sections $\sigma(e^+e^- \to f)$, where f are specific final states, differ considerably from one another (see the mini-review by Eidelman *et al.* [79]). For this reason, we briefly describe the apparent resonant activity in each final state. Just as in light-quark spectroscopy, mixing of quark-model configurations can lead to eigenstates favoring individual channels.

$\pi\pi J/\psi$ final state: The cross section for $e^+e^- \to \pi^+\pi^- J/\psi$, as first seen in the radiative return process $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ by the BaBar Collaboration [133] and confirmed in several other experiments [79], shows a prominent peak around 4260 MeV. It could be a $D\bar{D}_1$ state with about 25 MeV of binding energy [134]. Weaker evidence for a $J^{PC} = 1^{--}$ state around 4008 MeV presented by the Belle Collaboration [135] has not been confirmed by others. Recently the BESIII Collaboration has reported two new structures in $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$: one with a mass of (4222.0 ± 3.4) MeV and a broader one with a mass of (4320 ± 13) MeV [127] (Fig. 4). The first could be identified with a shifted $Y(4260)$, while the second has been proposed as an artifact of interference among $\psi(4160)$, $\psi(4415)$, and nonresonant background [136]. The lower $Y(4260)$ mass, with an asymmetric high-mass shoulder, was previously proposed based on the older data in the $D\bar{D}_1$ molecular model [137].

$\pi\pi\psi(2S)$ final state: Peaks in the effective mass of $\pi^+\pi^-\psi(2S)$ states have been seen by Belle and BaBar around 4360 and 4660 MeV [138, 129, 139, 130] (Fig. 4). The former ("$Y(4360)$") is roughly in the mass range expected for a charmonium 4S state, so the true 4S $c\bar{c}$ amplitude might be shared between the $Y(4360)$ and the $\psi(4415)$, with the rest of the $\psi(4415)$ wavefunction as a shallowly bound S-wave state of D_1 ($J^P = 1^+$) and D^* ($J^P = 1^-$). Alternatively, 4360 MeV is a plausible threshold for production of a $D(0^+)\bar{D}^*(1^-)$ pair. The latter ("$Y(4660)$") could be associated with a peak at a nearby mass, about 4630 MeV, in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ [132] (Fig. 4). The most precise data on the $\pi^+\pi^-\psi(2S)$ channel in the lower-peak region was recently published by BESIII (Fig. 4), which found a significant evidence for a state at 4.21 GeV, perhaps the same one as observed in the $\pi^+\pi^- J/\psi$ channel, and improved the $Y(4360)$ mass determination to 4384 ± 4 MeV [128].

$\pi\pi h_c$ final state: The $h_c(3525)$ is the lowest-lying ($n = 1$) n^1P_1 charmonium level, first seen by the CLEO Collaboration [140]. It is curious that, as a spin-singlet level, it should

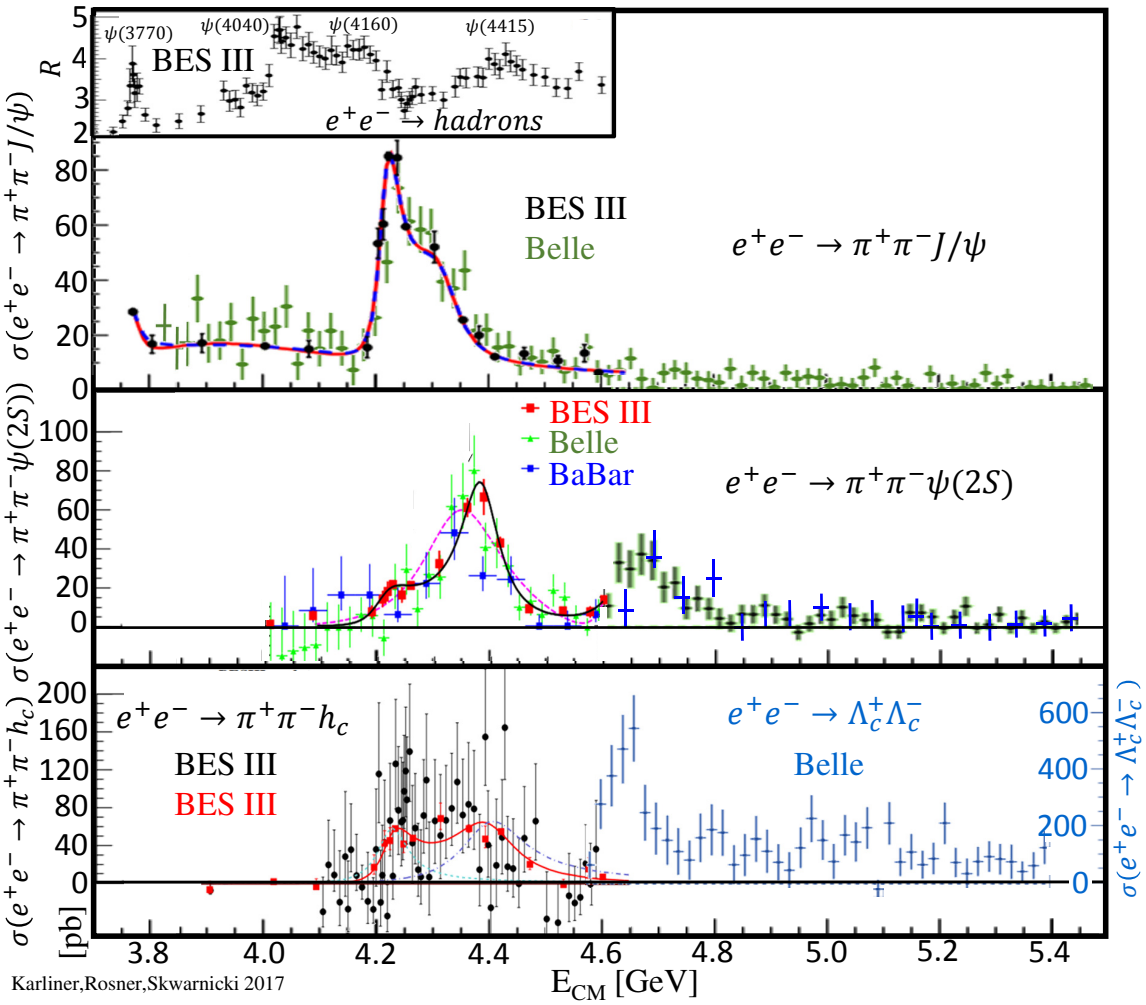

Figure 4: Measurements of cross-sections for e^+e^- annihilation: (top left inset) to hadrons expressed in units of R [125], (top row) to $\pi^+\pi^- J/\psi$ [127, 115], (middle row) to $\pi^+\pi^-\psi(2S)$ [128, 129, 130], (bottom row, left) to $\pi^+\pi^- h_c$ (black/red points are from two different energy scans by BESIII) [131], and (bottom row, right) to $\Lambda_c^+\Lambda_c^-$ [132]. The displayed curves were fitted to the BESIII data (see Refs. [127, 128, 131]).

have been produced in $e^+e^- \to \pi^+\pi^- h_c$, as first observed by the CLEO Collaboration [141] and reported recently by the BESIII Collaboration [131]. Normally one would expect a virtual photon to produce a $c\bar{c}$ spin-triplet state, so the process must be violating heavy-quark symmetry, perhaps via an intermediate open-flavor-pair state [113] in which the correlation between heavy-quark spins is lost. Two resonant structures are seen, one at 4218 ± 5 MeV and a broader one at 4392 ± 7 MeV (Fig. 4). The first is consistent with the BESIII observation in the $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$ final states mentioned above, while the second could be an artifact of interference among $\psi(4160)$, $\psi(4415)$, and nonresonant background [136].

Open charm final states: A comprehensive analysis of the behavior of the cross section for production of open charm final states has been made in Ref. [142]. The analysis supports the identification, mentioned above, of the $Y(4260)$ as mainly a molecular state of $D\bar{D}_1(2420)$. The resonance line shapes for $e^+e^- \to D^*\bar{D}^*$ and $e^+e^- \to D_s^*\bar{D}_s^*$ can be satisfactorily explained with contributions from $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, assuming suitable relative phases.

Resonances $\Upsilon(5S)$ and $\Upsilon(6S)$: The behavior of R above $B\bar{B}$ threshold exhibits two bumps, called $\Upsilon(5S)$ and $\Upsilon(6S)$, with respective masses 10890 ± 3 and 10993^{+10}_{-3} MeV [79]. An example of the shape of these bumps is given in Ref. [143]. Decay modes common to both include $B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$, $\pi\pi\Upsilon(1S, 2S, 3S)$, and $\pi\pi h_b(1P, 2P)$. As in the case of $Y(4260) \to \pi\pi h_c$, the latter class of decays violates heavy-quark symmetry and points to the role of open-flavor intermediate states [113]. The large decay widths for the transitions to $\pi\pi\Upsilon(nS)$ may be understood as enhancements of decay rates due to the intermediate states $Z_b(10610)$ and $Z_b(10650)$ [108]. Several other decay modes, including $f_0\Upsilon(1S)$, $\eta\Upsilon(1S, 2S)$, and $\pi^+\pi^-\Upsilon(1D)$, are reported for $\Upsilon(5S)$.

4.5 Other Exotic Meson Candidates Detected in B Decays

The first evidence for an explicitly exotic charged $Q\bar{Q}u\bar{d}$ state, $Z_c(4430)^+ \to \psi(2S)\pi^+$, was claimed by the Belle collaboration in $\bar{B} \to \psi(2S)\pi^+ K$ decays ($K = K^0_S$ or K^-) in 2007 [144], well before the other charged candidates were observed in $e^+e^- \to \pi^\mp Z^\pm_{b,c}$ (see Sec. 4.3). This state has a vivid experimental history. It was first claimed as a narrow peak ($\Gamma = 45^{+35}_{-18}$ MeV) in the invariant $\psi(2S)\pi^\pm$ mass distribution [144], with parameters obtained by a naïve fit to this distribution with ad hoc assumptions about the shape of the background from excited kaons, $K^* \to K\pi^+$, dominating such B decays. This observation was soon questioned by the BaBar experiment [145]. In response, the Belle experiment published amplitude analyses with a realistic model of K^* resonances, first performed on the Dalitz plane [146], later also including angular information from $\psi(2S) \to \ell^+\ell^-$ decays [147], which pointed to a significant $J^P = 1^+$ $Z_c(4430)^+ \to \psi(2S)\pi^+$ contribution, albeit much broader than initially claimed ($\Gamma = 200^{+49}_{-58}$ MeV). Later, the LHCb collaboration confirmed the Belle results in a similar amplitude analysis performed on a much larger sample of B decays [148], and demonstrated consistency of the $Z_c(4430)^+$ peak with a resonant hypothesis using an Argand diagram. They also demonstrated a need for other significant contributions than $K^{*0} \to K^-\pi^+$ to $\bar{B}^0 \to \psi(2S)\pi^+K^-$ decays without any assumptions about K^* resonances, other than limiting their spin in the relevant low $K^-\pi^+$ mass region [149].

The Belle collaboration claimed to have spotted $Z_c(4430)^+ \to J/\psi\,\pi^+$ in $\bar{B}^0 \to J/\psi\,\pi^+K^-$ decays, this time producing a dip in the $\psi(2S)\pi^+$ mass distribution via interference with an even broader ($\Gamma = 370^{+\ 99}_{-149}$ MeV) second 1^+ state, $Z_c(4200)^+ \to J/\psi\,\pi^+$, [150]. There was also some indication for a second $Z_c^+ \to \psi(2S)\pi^+$ state around that mass with 0^- or 1^+ quantum numbers in the LHCb data [148].

The Belle collaboration also reported evidence for charged $\chi_{c1}\pi^+$ resonances, the $Z_c(4050)^+$ and $Z_c(4250)^+$, in the amplitude analysis of $\bar{B}^0 \to \chi_{c1}\pi^+K^-$ decays, but could not determine their quantum numbers [151]. BaBar saw an enhancement in the same $\chi_{c1}\pi^+$ mass region, but suggested it could be a reflection of K^* resonances [152]. Without an amplitude analysis, their results do not contradict the Belle results.

As broad states, the charged Z_c^+ candidates are poor candidates for molecules of D and $\bar{D}$ excitations. They have not been reported in prompt production at the Tevatron or LHC, thus also making poor candidates for tightly bound tetraquark states. It is remarkable that they have not been observed in the $e^-e^+ \to \pi^\mp Z_c^\pm$ reaction; and, vice versa, the Z_c^+ states observed there have not been seen in B decays. This points to hadron-level forces responsible for these structures, perhaps via hadron rescattering in B decays, as such forces are expected to be sensitive to details of production mechanisms. Future high-statistics amplitude analyses of B decays in the upgraded LHCb and Belle experiments should shed more light on these effects.

The history of the $X(4140)$ state has some parallels to the $Z_c(4430)^+$ saga. It was first claimed in 2008 as a narrow peak ($\Gamma = 11.7^{\,+9.1}_{\,-6.2}$ MeV) observed by the CDF collaboration in the invariant $J/\psi\,\phi$ mass distribution from $B^+ \to J/\psi\,\phi K^+$ decays [153]. The existence of such a narrow, near-threshold state was questioned by the LHCb experiment [154]. The CMS experiment confirmed its existence, however, with somewhat larger width [155]. Later the LHCb experiment analyzed the biggest to date sample of $B^+ \to J/\psi\,\phi K^+$ decays, and performed the first amplitude analysis of this channel, thus providing more realistic subtraction of the $B^+ \to J/\psi\,K^{*+}$, $K^{*+} \to \phi K^+$ backgrounds [156, 157]. The LHCb data are consistent with a near-threshold $J/\psi\,\phi$ resonance, however, with a much broader width ($\Gamma = 83^{\,+30}_{\,-25}$ MeV) than initially measured. LHCb determined its quantum numbers to be $J^{PC} = 1^{++}$.

Since the 2011 update of the CDF analysis, there was a hint for a second $X(4274) \to J/\psi\,\phi$ state in the same B^+ decay mode [158]. A second $J/\psi\,\phi$ mass enhancement was visible in the CMS data, but at a higher mass [155]. The amplitude analysis by LHCb confirmed the $X(4274)$ state with high statistical significance and determined its quantum numbers to be also 1^{++} [156, 157]. Two 0^+ states at higher masses, $X(4500)$ and $X(4700)$, were also needed for a good description of the LHCb data.

The D0 experiment presented an evidence for prompt production of $X(4140)$ in $p\bar{p}$ collisions at Tevatron [159]. It is puzzling why the $X(4140)$ width observed in this inclusive measurements was narrow ($\Gamma = 16\pm13$ MeV) and why the $X(4274)$, $X(4500)$ and $X(4700)$ were not observed. This observation awaits a confirmation.

The Belle experiment, which was lacking statistics in the $B^+ \to J/\psi\,\phi K^+$ channel, looked for $J/\psi\,\phi$ states in $\gamma\gamma$ collisions. They obtained evidence for a narrow $X(4350)$ state ($\Gamma = 13^{+18}_{-10}$ MeV) and saw no other $J/\psi\,\phi$ mass peaks [160]. The $X(4350)$ state awaits confirmation as well.

The origin of the $J/\psi\,\phi$ states, among which the $X(4140)$ and $X(4274)$ should be

considered experimentally established, is far from clear. Their masses do not fall into the mass intervals near the pairs of excitations of the D_s ($\bar{D}_s$) mesons with **matching quantum numbers** for S-wave interactions, bound by η exchange [40]. Explanation of the $X(4140)$ as related to a $D_s^{\pm}D_s^{*\mp}$ cusp [161, 157], relies on broadening this threshold effect via a poorly justified form factor. Tightly bound tetraquark models can account for a doublet of 1^{++} states only in an approach in which "good" (color antitriplet) and "bad" (color sextet) diquarks are allowed [162]. In the tetraquark model using only "good" diquarks, it was suggested that $X(4274)$ is not a 1^{++} state but a superposition of two states with 0^{++} and 2^{++} [34]. However, such components of $X(4274)$ are disfavored by more than 7 standard deviations by the LHCb analysis (Table 7 in Ref. [157]). It was suggested that $X(4274)$, $X(4500)$ and $X(4700)$ states are conventional 3^3P_1, 4^3P_0 and 5^3P_0 charmonium states, respectively [163]. However, no explanation of why 4^3P_1 and 5^3P_1 states would not be also visible in the $J/\psi\,\phi$ decay mode was offered. None of the $X \to J/\psi\,\phi$ states observed in $B^+ \to J/\psi\,\phi K^+$ decays is seen in the $J/\psi\,\omega$ decay mode probed in $B^+ \to J/\psi\,\omega K^+$ decays (see Fig. 43 in Ref. [164]), suggesting that the $s\bar{s}$ pair is among the constituents of these states. With no plausible theoretical interpretation of all four of them together, they may have different origins or be some complicated artifacts of rescaterring of $D^{(*)}_{s(J)}$ meson-antimeson pairs. Future higher-statistics samples of $B^+ \to J/\psi\,\phi K^+$ decays may allow probing the nature of these structures in a less model-dependent way and shedding more light on their nature.

A near-threshold enhancement in the $J/\psi\,\omega$ mass distribution in $B \to J/\psi\,\omega K$ decays was first reported by Belle [165]. BaBar later resolved this structure into two mass peaks, identified with $X(3872) \to J/\psi\,\omega$ decay (Sec. 4.2) and the state at 3919 ± 4 MeV with rather narrow width, $\Gamma = 31 \pm 11$ MeV [87] (Fig. 1). Both Belle and BaBar observed a state at similar mass and width in $\gamma\gamma$ collisions [166]. It is commonly assumed, but not proven, that these mass structures are due to the same state as the one called $X(3915)$, with 0^{++} or 2^{++} as likely quantum numbers. This state is too narrow to be a conventional charmonium triplet P-state (for a full discussion see Ref. [164]) at masses where decays to $D\bar{D}^*$ and $D\bar{D}$ are allowed. It was recently proposed that mixing of the 2^3P_2 charmonium state with a molecular $D\bar{D}^*$ or $D^*\bar{D}^*$ component could be responsible for $X(3915)$ [167].

4.6 Quarkonium-like Pentaquark Candidates

A possibility of four quarks and one antiquark binding together was anticipated from the beginnings of the quark model [1], later reinforced by QCD, in which a diquark can effectively act as an antiquark, thus two diquarks and one antiquark can attract each other by the same means as three antiquarks do in an ordinary antibaryon. However, even today, we can't directly predict from QCD if such bound states can live long enough to have any measurable effects. Pentaquarks made only out of up and down quarks lack useful experimental signatures to distinguish them from ordinary baryons. Pentaquarks with a flavored antiquark would decay strongly to a baryon and a flavored meson, a final state which cannot be produced in a decay of an ordinary baryon. While some pentaquark candidates of that type were claimed in the past experiments, none of them survived scrutiny of additional data (see Secs. 2.2,3.2).

In 2015, the LHCb experiment observed a rather narrow ($\Gamma \sim 40$ MeV) structure in

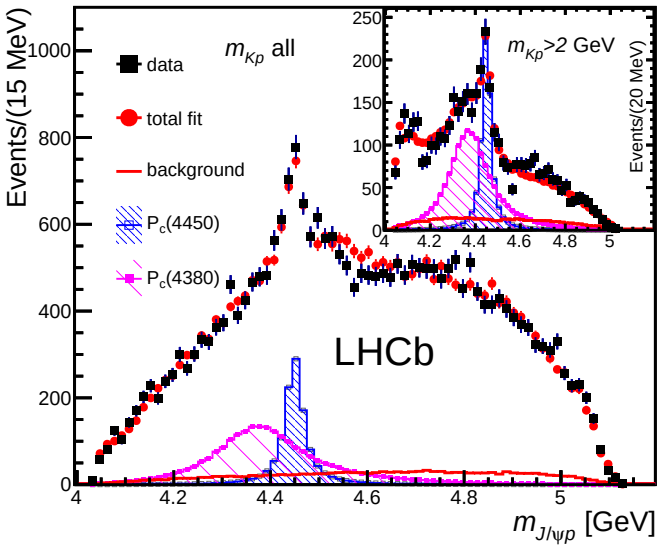

Figure 5: Observation of the pentaquark candidates $P_c(4450)^+$ and $P_c(4380)^+$ decaying to $J/\psi\, p$ in the amplitude analysis of $\Lambda_b \to J/\psi\, pK^-$ decays by the LHCb collaboration. Adapted from Ref. [168].

the $J/\psi\, p$ mass distribution in $\Lambda_b \to J/\psi\, pK^-$ decays [168], as shown in Fig. 5. Since the heavy $c\bar{c}$ pair in the J/ψ cannot be created during hadronization with rates which would lead to such observation, this structure makes for a convincing $uudc\bar{c}$ candidate. Its statistical significance is much larger than any of the previous pentaquark candidates, thus this effect is not going to fade away with additional data. LHCb demonstrated at the 9σ level that the $J/\psi\, p$ mass peak cannot be due to reflections of excited Λ states decaying to pK^-, with almost no assumptions about such Λ^* baryons, which dominate this Λ_b decay mode [169]. An amplitude analysis of these data, which used 13 well established Λ^* resonances as a model for the pK^- component, revealed that two $J/\psi\, p$ resonances were needed for a reasonable description of data: the narrow $P_c(4450)^+$ ($\Gamma = 39 \pm 20$ MeV) and the lighter and wider $P_c(4380)^+$ ($\Gamma = 205 \pm 88$ MeV). Both states had a very high statistical significance (12σ and 9σ, respectively), albeit depending on much stronger model assumptions [168]. The Dalitz plot pattern of their intensities implies they should have opposite parities. The spin combinations involving 3/2 and 5/2, in either order, were preferred. In addition to pentaquarks with $uudc\bar{c}$ quarks bound together in one confining volume by color forces, also baryon-meson molecules bound by residual color forces, similar to those responsible for creation of nuclei, can have the same quark content. In fact, a $\Sigma_c\bar{D}^*$ molecular state was predicted by Karliner and Rosner around the $P_c(4450)^+$ mass [39]. This model requires $J^P = 3/2^-$ and provides a natural explanation for its narrow width. The $p\chi_{c1}$ mass threshold coincides with the $P_c(4450)^+$ mass [170]. Such a molecular state, or cusp, would require $J^P = 3/2^+$. Molecular bound states or cusps don't offer any explanation for the broad $P_c(4380)^+$ state, nor can they lead to spin as high as 5/2 in this mass range. Rescattering of ordinary baryons and mesons,

via the so-called triangle anomaly, must happen in an S-wave to be pronounced, thus cannot account for spin 5/2 either [171, 172, 43]. The tightly bound pentaquark model can generate such high spin for $P_c(4450)^+$ via orbital angular momentum between quarks [33] and can account for the wider $P_c(4380)^+$. So far, the rich mass spectrum necessarily resulting from such quark confinement has not been experimentally observed. It is also not clear why such a pentaquark state would be narrow, with the large phase-space available for $J/\psi\, p$ decays and the spatial proximity of c and $\bar{c}$. It was suggested that momentary separation of c and $\bar{c}$, followed by immediate hadronization, can be a result of a production mechanism pushing them in opposite directions [173]. Such a cartoon model is lacking predictive power, thus is difficult to confirm or dismiss. The LHCb Collaboration did not assign statistical or systematic significance to the determined quantum number preference. Therefore, it is premature to draw strong conclusions about possible interpretations of the P_c^+ states based on this preference. It is more than likely that the LHCb model of the Λ^* states was incomplete, since about 60 Λ^* states are predicted in the relevant mass range by the quark model [168], and in fact some of them were observed in various analyses of the KN scattering data, but were too model-dependent to earn labels of well-established states by the PDG [25]. Coupled channels, especially $(\Sigma\pi)_{I=0}$, are likely to make significant contributions as well. More $\Lambda_b \to J/\psi\, pK^-$ data are already available to LHCb. It is hoped their improved amplitude analysis will shine more light on the nature of these $J/\psi\, p$ mass structures.

The LHCb analyzed also the Cabibbo-suppressed channel $\Lambda_b \to J/\psi\, p\pi^-$ [174]. With much fewer events, complications from many known $p\pi^-$ resonances, and the possibility of an exotic contribution from the $Z_c(4200)^- \to J/\psi\, \pi^-$ state, the results were inconclusive. The data are fully compatible with the $P_c(4380)^+$ and $P_c(4450)^+$ contributing to this final state at the expected level, but also compatible with no such contributions if the $Z_c(4200)^-$ is allowed.

There have been no claims of spotting the P_c^+ states in prompt production at LHC, which would have favored a tightly bound pentaquark model. Molecular or tightly bound $J/\psi\, p$ states should be reachable in photoproduction at JLab [175], where several experimental searches for them are under way.

5 BEYOND DETECTED STATES

$QQ\bar{Q}\bar{Q}$:

The question of whether there exist bound states of two heavy quarks $Q = (c, b)$ and antiquarks $\bar{Q} = (\bar{c}, \bar{b})$, distinct from a pair of quark-antiquark mesons, has been debated for more than forty years. It has drawn substantial interest recently [176, 177, 178]. Ref. [176] predicted $M(X_{cc\bar{c}\bar{c}}) = 6{,}192 \pm 25$ MeV and $M(X_{bb\bar{b}\bar{b}}) = 18{,}826 \pm 25$ MeV, for the $J^{PC} = 0^{++}$ states involving charmed and bottom tetraquarks, respectively. Earlier predictions vary over a big range, with large error bars, cf. Table VII in Ref. [176]. A more recent compilation of predicted values of $M(X_{bb\bar{b}\bar{b}}) - 2M(\eta_b)$ appears in Table I of Ref. [177]. The proximity of the predicted $X_{bb\bar{b}\bar{b}}$ mass to $2M(\eta_b) = 18,798 \pm 5$ MeV [25] and the size of the theoretical errors suggests that $X_{bb\bar{b}\bar{b}}$ either decays strongly with a rather narrow width, or it is below the $\eta_b\eta_b$ threshold, in which case one expects final

states of hadrons from pairs of intermediate gluons, and of hadrons or leptons from pairs of intermediate virtual photons. Experimental search for these states in the relevant mass range is highly desirable. Searches in the four-lepton and $\ell^+\ell^- B\bar{B}$ final states have been performed at the LHC [179]. These are devoted to the search for the standard-model Higgs boson decaying into two light pseudoscalars a, which then decay to such final states as $\mu^+\mu^-$, $\tau^+\tau^-$, and $b\bar{b}$. These are ideal samples for the searches advocated here.

Bottom analogues of $D^*_{s0}(2317)$ and $D_{s1}(2460)$:

These B_{sJ} states are the yet-to-be-discovered b-quark analogues of the very narrow D_{sJ} states seen by BaBar, CLEO and Belle [58, 59, 60, 61] $D_{s0}(2317)$ with $J^P = 0^+$ and $m[D_{s1}(2460)]$ with $J^P = 1^+$, conjectured to be the chiral partners of D_s, $J^P = 0^-$ and D^*_s, $J^P = 1^-$, respectively [71, 72]. A strong hint toward this conjecture is supplied by almost equal splitting between the states of opposite parity [25]: $m[D_{s0}(2317)] - m[D_s]$=349.4 $\pm$ 0.6 MeV$\approx m[D_{s1}(2460)] - m[D^*_s]$= 347.3 $\pm$ 0.7 MeV$\approx$ constituent mass of light quarks. Assuming approximately the same splitting in the bottom sector, one expects B_{s0} at $\sim$ 5717 MeV with $J^P = 0^+$ and B_{s1} at $\sim$ 5765 MeV with $J^P = 1^+$. They are also predicted by a lattice calculation [180]. These states are likely to be observed at LHCb and might also be accessible at Belle II in $e^+e^- \to B_{s0}\bar{B}^*_s$ and $e^+e^- \to B_{s1}\bar{B}_s$ [181].

Stable $bb\bar{u}\bar{d}$ tetraquark:

Recently LHCb discovered the first doubly-charmed baryon $\Xi^{++}_{cc} = ccu$ at 3621.40 $\pm$ 0.78 MeV [182], very close to the theoretical prediction 3627 $\pm$ 12 MeV in Ref. [183].[3] In Ref. [184] the same theoretical approach was used to predict a doubly-bottom tetraquark $T(bb\bar{u}\bar{d})$ with J^P=1^+ at $10,389 \pm 12$ MeV, 215 MeV below the $B^-\bar{B}^{*0}$ threshold and 170 MeV below threshold for decay to $B^-\bar{B}^0\gamma$. Similar conclusions were obtained in Refs. [185]. The $T(bb\bar{u}\bar{d})$ is therefore stable under strong and electromagnetic (EM) interactions and can only decay weakly, the first exotic hadron with such a property. The predicted lifetime is $\tau(bb\bar{u}\bar{d}) \sim 367$ fs. The $T(bb\bar{u}\bar{d})$ tetraquark can decay through one of two channels:
(a) The "standard process" $bb\bar{u}\bar{d} \to cb\bar{u}\bar{d} + W^{*-}$. Typical reactions include $T(bb\bar{u}\bar{d}) \to D^0\bar{B}^0\pi^-$, $D^+B^-\pi^-$ and $T(bb\bar{u}\bar{d}) \to J/\psi\, K^-\bar{B}^0$, $J/\psi\, \bar{K}^0 B^-$. In addition, there is a rare process where *both* b quarks decay into $c\bar{c}s$, $T(bb\bar{u}\bar{d}) \to J/\psi\, J/\psi\, K^-\bar{K}^0$. The signature for events with two J/ψ's coming from the same secondary vertex might be sufficiently striking to make it worthwhile to look for such events against a large background.
(b) The W-exchange process $b\bar{d} \to c\bar{u}$, involving either one of the two b quarks. The latter process can involve a two-body final state, e.g., $T(bb\bar{u}\bar{d}) \to D^0B^-$.

In contrast with $T(bb\bar{u}\bar{d})$, the mass of $T(cc\bar{u}\bar{d})$ with J^P=1^+ is predicted to be 3882$\pm$12 MeV, 7 MeV *above* the D^0D^{*+} threshold and 148 MeV above $D^0D^+\gamma$ threshold. $T(bc\bar{u}\bar{d})$ with J^P=0^+ is predicted at 7134 $\pm$ 13 MeV, 11 MeV below the $\bar{B}^0D^0$ threshold. The theoretical precision is not sufficient to determine whether $bc\bar{u}\bar{d}$ is actually above or below the threshold. It could manifest itself as a narrow resonance just at threshold.

At this point it is interesting to point out an interesting pattern: the known candidates for hadronic molecules are hidden-flavor quarkonium-like states $Q\bar{Q}q\bar{q}$, $Q = b, c$, $q = u, d$, while the stable tetraquark belongs to the open-flavor $QQ\bar{q}\bar{q}$ category. There is a good

[3] We refer the reader to Refs. [182] and [183] for an extensive list of other predictions, most of which quote much greater uncertainties.

reason for this pattern.

$T(bb\bar{u}\bar{d})$ is below two-meson threshold because the two heavy quarks are very close to each other ∼0.2 Fermi. They form a color antitriplet and attract each other very strongly. Consider a typical Coulomb + linear Cornell-like potential $V(r) = -\alpha_s/r + \sigma r$. At ∼0.2 Fermi the heavy quarks probe the Coulomb, singular part of the potential, so the binding energy is very large, ∼280 MeV. But the tightly-bound (bb) sub-system is a color antitriplet, so it cannot disconnect from the two light antiquarks. Hence the tetraquark is bound vs. two heavy-light $b\bar{q}$ mesons which lack the strong attraction between the two heavy quarks.

The situation is completely different in bottomonium-like system $(b\bar{b}q\bar{q})$: the lowest energy configuration of the $(b\bar{b})$ subsystem is a color singlet. So when b and $\bar{b}$ get close, they decouple from the light quarks and form an ordinary bottomonium. In other words, in a $(b\bar{b}q\bar{q})$ system there is no possibility of utilizing the very strong attraction between b and $\bar{b}$ without at the same time forcing the system to decay into quarkonium and pion(s).

This is why exotic bottomonium-like states have a completely different structure – they are hadronic molecules of two heavy-light mesons bound by exchange of light hadrons. Such molecules have a mass which is much higher than their decay products: For example, $Z_b(10610)$ is ∼1 GeV above $\Upsilon(1S)\pi$ threshold. Nonetheless, they have a strikingly narrow width despite such a large phase space, e.g., $\Gamma(Z_b(10610)) \sim 20$ MeV [186]. The reason is that in order to decay into quarkonium and a pion the two heavy quarks must get very close to each other. In a large deuteron-like molecular state the probability for such a close encounter is quite small, analogous to the small probability for an electron to be inside the proton in the ground state of a hydrogen atom.

Analogous comments apply to $cc\bar{q}\bar{q}$ states vs. $c\bar{c}q\bar{q}$, states, with an important difference that $m_c/m_b \sim 1/3$, so the substantial binding energy of the (cc) subsystem is nevertheless significantly smaller that in (bb) subsystem and therefore $cc\bar{q}\bar{q}$ is likely unbound with respect to two $(c\bar{q})$ mesons.

6 SUMMARY AND OUTLOOK

The quark model has been highly successful in describing the spectroscopy of mesons and baryons as quark-antiquark $(q\bar{q})$ and three-quark (qqq) systems, respectively. With the u, d, s quarks assigned the fractional charges $2/3, -1/3, -1/3$, these are the simplest states with integral charges. However, the model also implied the existence of more complicated states with integral charges, such as $qq\bar{q}\bar{q}$ mesons and $qqqq\bar{q}$ baryons [1]. Regarding quarks as fundamental triplets of a color SU(3) symmetry, the color-singlet states have integral charges. Why weren't these "exotic" states seen?

One signal of an exotic hadron is its "flavor" quantum numbers, calculated from the charge $(2/3, -1/3, -1/3)$ and strangeness $(0, 0, -1)$ of the u, d, s quarks. Thus, a meson with the quantum numbers of $uu\bar{s}\bar{s}$, decaying to K^+K^+ or $p\bar{\Xi}^+$, would be manifestly exotic, as its charge and strangeness could not be exhibited by any $q\bar{q}$ state. Similarly, a baryon with the quantum numbers of $uudd\bar{s}$, decaying to K^+n or K^0p, would be manifestly exotic.

Various models implied that exotic states of u, d, s quarks existed, but were not iden-

tifiable either because they did not possess exotic flavor quantum numbers or because they were too broad to be distinguishable from two-hadron continuum states. A model in which quarks were confined by a quantum-chromodynamics "bag" [26] predicted a $qq\bar{q}\bar{q}$ meson as light as a few hundred MeV but with large decay width to $\pi\pi$. Narrower exotic mesons now known as f_0 and a_0 were expected with masses about a GeV, as seen, but their flavor quantum numbers are indistinguishable from those of $q\bar{q}'$ states. In the bag model they possess an additional $s\bar{s}$ pair in their wave functions, and thus are known as "crypto-exotic." The application of quark-hadron duality to baryon-antibaryon scattering implied that t-channel exchanges of (non-exotic) $q\bar{q}$ states were dual to (exotic) $qq\bar{q}\bar{q}$ states in the s channel [28]. Thus, one expected exotic states in baryon-antibaryon channels, such as $\Delta^{++}\bar{n}$ and $\bar{\Lambda}p\pi^+$. Their absence may be ascribed to their large decay widths.

The situation has changed with the advent of the heavy charm (c) and bottom (b) quarks. A multitude of exotic hadrons with two or more heavy quarks have been seen, starting with the $X(3872)$ [35], where the number in parentheses refers to the mass in MeV. Several mechanisms appear to be at work in these observations. In the case of the $X(3872)$, one-pion-exchange between a charmed meson D and an anti-charmed meson $\bar{D}^*$, binding them into a bound or virtual S-wave state, plays a crucial role. The spin J, parity P, and charge-conjugation eigenvalue C of the state are then expected to be $J^{PC} = 1^{++}$, as observed. The isospin splitting between neutral and charged charmed mesons ensures that the meson-antimeson component of the X wave function is mainly $D^0\bar{D}^{*0}$, so it is a mixture of isospins zero and one with quark content $c\bar{c}u\bar{u}$. Its decay to $J/\psi\gamma$ and $\psi(2S)\gamma$ implies that it has some $c\bar{c}$ in its wave function. It would then be a mixture of a molecular state and the first radial excitation of the $\chi_{c1}(1P)$ state. [The notation is that of Ref. [25]].

The name "tetraquark" conventionally refers to a state in which all quarks and antiquarks participate democratically in binding. For the $X(3872)$ to be identified as a tetraquark, the grouping into a charmed meson-antimeson pair has to be ignored, and there has to be a charged partner with the same J^P nearby in mass. The $Z_c(3900)$ would have been a possible candidate except that it has $C = -$ instead of $C = +$ [79]. In the absence of full isospin multiplets, one cannot yet identify many exotic hadrons as tetraquarks or pentaquarks.

The bottom counterpart of the $X(3872)$ has yet to be identified. It may participate in some mixing with a state thought to be the $\chi_{b1}(3P)$ [102]. Because its constituent B and $\bar{B}^*$ mesons enjoy little isospin splitting, its isospin is expected to be mainly zero, so it should decay to $\Upsilon(1S, 2S, 3S)\omega$, unlike $X(3872)$ which decays both to $J/\psi\,\omega$ and $J/\psi\,\rho$ [104].

Strong candidates for molecular states also exist in the bottom sector. The masses of $Z_b(10610)$ and $Z_b(10650)$ are very close to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, respectively. They are seen not only in the $\Upsilon(1S, 2S, 3S)\pi$ channels (only charged pion for $Z_b(10650)$), but also in the $h_b(1P, 2P)\pi^\pm$ channels, implying a violation of heavy-quark symmetry [113]. This is to be expected if the wave functions of the states are mainly meson-antimeson. The important role of pion exchange in creating these states is supported by the absence of states near $B\bar{B}$ threshold.

A number of exotic meson candidates with $c\bar{c}$ accompanied by light quarks have been

seen in the 4–5 GeV mass range. Many of these cannot be associated with specific thresholds, and their tetraquark interpretation often awaits discovery of their isospin counterparts. In channels where pion exchange is not possible, the role of η exchange remains to be tested [40].

A prominent feature of charmed-pair production by e^+e^- collisions is its rapid drop just above a center-of-mass energy of 4.2 GeV, recalling similar behavior in the $\pi\pi$ $I = J = 0$ channel just around $K\bar{K}$ threshold. In the charm case the behavior is likely to be correlated with the threshold for $D(2420)\bar{D}$ production, which is the lowest-lying charmed pair which can be produced in an S wave. It illustrates the importance of S-wave thresholds, which appear in a wide variety of cases in particle physics and elsewhere [124, 48].

After a couple of false starts (by others) in searches for $qqqq\bar{q}$ states, the LHCb experiment has observed two in the $J/\psi p$ channel, produced in the decay $\Lambda_b \to J/\psi K^- p$: a narrow one around 4450 MeV and a much broader one around 4380 MeV, with opposite parities and preference for 3/2 and 5/2 spins, in either order. A $\Sigma_c\bar{D}^*$ molecule with properties consistent with the $P_c(4450)$ state has been suggested [39], but a molecular interpretation of the lower, broader, state is elusive. A genuine pentaquark interpretation would imply the states are accompanied by numerous isospin partners, not yet observed.

A general feature of exotics with two or more heavy quarks is the reduction in kinetic energy afforded by their large masses. This, together with their shorter Compton wavelength leading to deeper binding, implies that states incorporating those heavy quarks may be deeply enough bound to overcome the tendency to "fall apart" exhibited by exotic states composed only of u, d, s quarks. An extreme example of this is the prediction of a bound $bb\bar{u}\bar{d}$ state [184, 185], supported by methods used in the successful prediction of the mass of a baryon containing two charm quarks [183].

Looking back at the experimental developments in hadron spectroscopy in the new millennium: heavy quarks have done it again! After converting us into firm believers of the quark model in the seventies, heavy quark systems have more recently taught us a new lesson: not all hadronic states are the minimal quark combinations. In addition to $q\bar{q}$ mesons, four-quark $qq\bar{q}\bar{q}$ configurations become important, especially near and above the $q\bar{q}$ plus $q\bar{q}$ meson thresholds. Similarly, not all baryons are qqq states; $qqqQ\bar{Q}$ configurations also play a role. Theoretical disputes rage on, if the observed multiquark configurations are tightly bound tetra- and penta-quarks, or loosely bound meson-meson and baryon-meson molecules. In our opinion, the case for the latter is stronger. It is also beyond any dispute that baryon-baryon molecules exist and have been known for a long time as nuclei. This does not imply that every multiquark system must be loosely bound. In fact, the models which work well for doubly-charmed baryons also predict a stable $bb\bar{u}\bar{d}$ tightly bound tetraquark.

What does the future hold for exotic multiquark mesons and baryons? As mentioned, the photoproduction of $J/\psi p$ resonances is possible at JLAB. Production of charmonium-like states is envisioned at PANDA. We are likely to be surprised by more charmonium-like exotics from Belle II and LHCb. After its upgrades, the LHCb may have a shot at the $bb\bar{u}\bar{d}$ tetraquark. We are looking forward to these developments!

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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