Topics in Hadron Spectroscopy in 2009

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There have been numerous developments in hadron spectroscopy over the past year. In this brief review I focus on two general areas. In the first I give an update on hadrons with \( b \)-quarks. Their properties are in textbook agreement with QCD motivated constituent quark models. The second topic is the Charmonium-like \( XYZ \) states above open charm threshold that continue to be discovered. Many of these do not seem to be described as conventional \( c \bar{c} \) states and may be hadronic molecules, Tetraquarks, or Charmonium Hybrids. The first topic is an example of how well we seem to understand hadrons while the second case reminds us of how much we still have to learn.

1. Introduction

There have been many developments in hadron spectroscopy during the past year. It is impossible to do justice to all them in a brief review. I will focus on two topics: new hadrons with \( b \) quarks and the so called charmonium \( X \), \( Y \), \( Z \) states, many of which do not seem to be understood as conventional hadrons. There are many other developments that deserve attention but which I will not discuss: the \( f_D \), puzzle and possible hints for new physics, the \( \Upsilon(2175) \) and \( \Upsilon(10890) \) states, further measurements of \( B_c \) properties, new measurements of hadronic transitions in quarkonium, recent results by the BESIII collaboration on \( J/\psi \) decays, the \( N^* \) program at Jefferson Lab, new measurements of quarkonium annihilation decays, etc. etc.. I apologize for the many interesting topics I am not able to cover in a brief update. Some recent reviews of hadron spectroscopy are given in Ref. \cite{1,2,3,4,5}.

Quantum Chromodynamics (QCD) is the theory of the strong interactions but it has been a challenge to calculate the properties of hadrons directly from the QCD Lagrangian in the regime where the theory is non-perturbative. Instead, alternative approaches have been used; Lattice QCD, effective field theories, chiral dynamics, and the constituent quark model. Measurement of hadron properties provide an important test of these calculational approaches. On the one hand, there has been much progress in recent years, while on the other hand, a large number of states have been discovered with properties that are not easily or consistently explained by theory.

In this context I use the constituent quark model (CQM) as a benchmark against which to identify and compare the properties of the newly discovered states \cite{6}. Constituent quark models typically assume a QCD motivated potential that includes a Coulomb-like one-gluon-exchange potential at small separation and a linearly confining potential at large separation. The potential is included in a Schrodinger or relativistic equation to solve for the eigenvalues of radial and orbital angular momentum excitations. For the case of mesons, the quantum numbers are characterized by \( J^P_C \) quantum numbers where \( S \) is the total spin of the quark-antiquark system, \( L \) is the orbital angular momentum, \( P = (-1)^L+1 \), and for self-conjugate mesons, \( C = (-1)^L S \). With these rules, the quark model predicts the allowed quantum numbers of \( J^P_C = 0^+, 1^−, 1^+, 0^+, 1^−, 1^+, 2^+ \ldots \). Quantum numbers not allowed by the CQM such as \( J^P_C = 0^−, 0^+, 1^−, 1^+ \), and \( 2^+ \), are often referred to as exotic combinations and, if such states were discovered, would unambiguously signify hadronic states outside the quark model.

In addition to the spin-independent potential there are spin-dependent potentials that are relativistic corrections, typically assuming a Lorentz vector one-gluon-exchange and a Lorentz scalar confining potential. This leads to a short distance spin-spin contact interaction which splits the spin-triplet and spin-singlet \( S \)-wave states. If the spin-spin interaction were not short range it would result in a splitting between the spin-singlet and spin-triplet centre of gravity of the \( L \neq 0 \) states. There is also a spin-spin tensor interaction which contributes to splittings in \( S = 1 \), \( L \neq 0 \) multiplets in addition to mixings between states with the same \( J^P_C \) quantum numbers. Finally, there are spin-orbit interactions that contribute to splittings between \( S = 1 \), \( L \neq 0 \) states and mix states with unequal quark and antiquark masses where \( C \) is not a good quantum number and with the same \( J^P \) such as \( 3P_1 \) \( -1 \) \( P_1 \) pairs. The tensor and spin-orbit interactions give rise to the splittings in, for example, the \( \chi_{c0}, \chi_{c1}, \chi_{c2} \) multiplet. Strong Zweig allowed decays, annihilation decays, hadronic transitions, and electromagnetic transitions have also been calculated using various models \cite{7,8}. Putting all these predictions together one can build up a fairly complete picture of a quark model state’s properties that can be compared to experimental measurements.

In addition to these conventional CQM hadrons, models of hadrons predict the existence of additional states:

**Hybrids** are states with an excited gluonic degree of freedom. Some hybrids are predicted to have exotic quantum numbers which would signal a
non-qq state. Almost all models of hybrids predict that hybrids with conventional quantum numbers will have very distinctive decay modes that can be used to distinguish them from conventional states.

**Multiquark States** Molecular States are a loosely bound state of a pair of mesons near threshold. One signature of these states is that they exhibit large isospin violations. Tetraquarks are tightly bound diquark-diantiquark states. A prediction of tetraquark models is that they are predicted to come in flavour multiplets.

Threshold-effects come about from rescattering near threshold due to the interactions between two outgoing mesons. They result in mass shifts due to thresholds. A related effect are coupled channel effects that result in the mixing of two-meson states with qq resonances.

One can think of an analogy in atomic physics for multiquark states and hybrids. Say we know about atomic spectroscopy but theorists predict something they call molecules that have never been discovered. Whether molecules really exist would be an important test of theory. Likewise, the unambiguous discovery of hybrids and multiquark states is an important test of our models of QCD.

2. Bottomonium ηb State

The observation of the ηb is an important validation of lattice QCD and other calculations. One means of producing the ηb is via radiative transitions, specifically M1 transitions from the nS1(bb) states [7, 8].

The partial width for this transition is given by

\[
\Gamma(\eta_b) = \frac{4}{3} \alpha \frac{e^2}{m_Q} |(f|j_0(kr/2)|i)|^2 k^3 \gamma
\]

where \(e_Q\) is the quark charge in units of \(e\), \(m_Q\) is the mass of the quark, \(k_\gamma\) is the energy of the emitted photon, and \(j_0\) is the spherical Bessel function. Hindered decays are those that occur between initial and final states with different principle quantum numbers. In the non-relativistic limit, the wavefunctions are orthogonal so that these decays are forbidden. However, hindered decays have large phase space so that even small deviations from the non-relativistic limit can result in observable decays. In contrast, the allowed transitions have very little phase space so the partial widths are likely to be too small to be observed.

Last year the BaBar collaboration announced the discovery of the ηb(1S0) state in the transition \(\Upsilon(3S) \to \eta_b \gamma\) [9] with \(B(\Upsilon(3S) \to \eta_b \gamma) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}\). More recently BaBar confirmed the ηb in the transition \(\Upsilon(2S) \to \eta_b \gamma\) with \(B(\Upsilon(2S) \to \eta_b \gamma) = (4.2^{+1.0}_{-1.0} \pm 0.9) \times 10^{-4}\) [10]. The photon spectrum for this transition is shown in Fig 1. The average ηb mass from the two measurements is

\[
M(\eta_b) = 9390.4 \pm 3.1 \text{ MeV} \quad (2)
\]

This is in agreement with Lattice QCD and the predictions of QCD based models. After the DPF conference, the CLEO collaboration [11] reported evidence for the ηb in \(\Upsilon(3S) \to \eta_b \gamma\) with statistical significance of \(\sim 4\sigma\) and with \(M(\eta_b) = 9391.8 \pm 6.6 \pm 2.0 \text{ MeV}\) and \(B(\Upsilon(3S) \to \eta_b \gamma) = (7.1 \pm 1.8 \pm 1.2) \times 10^{-4}\) which are consistent with the BaBar measurements. Both the measured mass and branching ratios support the models of heavy quarkonium spectroscopy.

3. Bottomonium Υ(1D) State

Another bb state I want to mention is the Υ(1D) state. It was suggested that the Υ(1D) states could be observed in the cascade decays consisting of four E1 transitions in the decay chain \(3S1 \to \Xi_7 \to 1^3D_f \to 1^3P_f \to 1^3S_1\) [12, 13]. The E1 partial widths and branching ratios can be estimated using the quark model. The CLEO collaboration followed this search strategy and observed an Υ(1D) [14]. The data are dominated by the production of one Υ(1D) state consistent with the \(J = 2\) assignment. It was measured to have a mass of \(M = 10161.1 \pm 0.6 \pm 1.6 \text{ MeV}\) which is in good agreement with predictions of potential models and Lattice QCD. The measured BR for the decay chain is \(B = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5}\) which compares well to the predicted BR of \(B = 2.6 \times 10^{-5}\).

This result is not exactly a new result. I mention it because CLEO’s discovery was based on an Υ(3S) data sample of \(5.8 \times 10^6\) Υ(3S). In contrast, BaBar has collected a sample of \(109 \pm 1 \times 10^6\) Υ(3S)’s, almost 20 times the size of the CLEO sample. BaBar has the
potential to observe all three of the $1^3D_J$ states which would be a nice test of our understanding of the $3D_J$ splittings.

4. Baryons with $b$ Quarks

In the last year a number of baryons with $b$-quarks were observed for the first time by the D0 [15] and CDF collaborations [16]. The ground state baryons with $b$ quarks and their quark content are given by:

$$
\Lambda_b^0 = |bud\rangle \\
\Sigma_b^{(*)+, -} = |buu\rangle \\
\Xi_b^{(*)-} = |bsd\rangle \\
\Omega_b^{(*)} = |bss\rangle
$$

The splittings of the ground state baryons can be described reasonably well by only including the colour hyperfine interaction between two quarks [17]:

$$
\Delta H_{ij}^{hyp} = \frac{16\pi\alpha_s}{9m_im_j} \frac{\vec{S}_i \cdot \vec{S}_j}{m_im_j} \langle \delta^3(\vec{r}_{ij}) \rangle \sim \gamma \frac{\vec{S}_i \cdot \vec{S}_j}{m_im_j}
$$

where we made the simplifying approximation that the wavefunction at the origin and $\alpha_s$ are roughly the same for all states. This results in a number of predictions

$$
M(\Sigma_b^0) - M(\Sigma_b) = [M(\Sigma_b^0) - M(\Sigma_b)] \times \frac{m_c}{m_b} \simeq 25 \text{ MeV}
$$

$$
M(\Sigma_b) - M(\Lambda_b) = [M(\Sigma_b^0) - M(\Sigma_b)] \times \frac{1 - \frac{m_u}{m_c}}{1 - \frac{m_s}{m_c}} \simeq 192 \text{ MeV}
$$

5. The Charmonium like $X$, $Y$, $Z$ States

Over the last five years or so, numerous charmonium like states have been discovered with many of them not fitting into conventional charmonium spectroscopy [1, 2, 4, 5]. This has led to considerable theoretical speculation that some of these new states are non-conventional hadrons like hybrids, molecules,
or tetraquarks, or possibly some sort of threshold effect. More and more of these states seem to appear every other day and it is far from clear what most of them actually are. The charmonium spectrum is summarized in Fig. 5. This is a very cluttered figure which underlines the complexity of the current situation. A more detailed summary of these states is given in Table I.

One can see that there are many of these charmonium like states. I will restrict myself to the following; I will start with the most recently observed states, the Y(4140) seen by CDF [22] and the X(3915) seen by Belle [5]. I will next report on the Z+ states, charmonium-like states observed by Belle that carry charge so cannot be conventional c ¯ c states. I will then briefly discuss the X(3872) which was the first charmonium-like state to be observed and is the most robust, having been observed by many experiments in different processes. The final group is the 1−− Y states observed in e+e− → γISR + Y.

5.1. The Y(4140)

The CDF collaboration found evidence for the Y(4140) in the J/ψφ invariant mass distribution from the decay B+ → J/ψφK+ which is shown in Fig. 6 [22]. The state has significance of 3.8σ with M = 4143.0 ± 2.9 ± 1.2 MeV/c² and Γ = 11.7+8.3−5.0 ± 3.7 MeV/c². Because both the J/ψ and φ have J P C = 1−− the Y(4140) has +ve C parity. Some argue that there are similarities to the Y(3940) seen in B → J/ψωK [24].

The question asked about all these new XYZ states is: What is it? And as in all of these states, we consider the different possibilities, comparing the state’s properties to theoretical predictions.

Conventional State The Y(4140) is above open charm threshold so it would be expected to have a large width which is in contradiction to its measured width. Hence, the Y(4140) is unlikely to be a conventional c ¯ c state.

c ¯ c ¯ s ¯ s Tetraquark A number of authors argue that the Y(4140) is a tetraquark [23, 26, 27]. However a tetraquark is expected to decay via rearrangement of the quarks with a width of ∼ 100 MeV. It is also generally expected to have similar widths to both hidden and open charm final states. The tetraquark interpretation does not, therefore, appear to be consistent with the data.

Charmonium Hybrid Charmonium hybrid states are predicted to have masses in the 4.0 to 4.4 GeV mass range. The Y(4140)’s mass lies in this range. Hybrids are expected to decay predominantly to SP meson pair final states with decays to SS final state meson pairs suppressed. If the Y(4140) were below D*+D threshold the allowed decays to DD would be suppressed leading to a relatively narrow width. The D*+D is an
Table I Summary of the Charmonium-like XYZ states.

| state         | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Seen In                                      | Observed by:                          | Comments                        |
|---------------|-----------|----------------|----------|---------------------------------------------|----------------------------------------|----------------------------------|
| $Y_c$(2175)   | 2175 ± 8  | 58 ± 26        | 1$^-$   | $(e^+e^-)_{ISR,J/\psi} \rightarrow Y_c$(2175) $\rightarrow \phi f_0$(980) | BaBar, BESII, Belle                   |                                  |
| $X$(3872)     | 3871.4 ± 0.6 | < 2.3      | 1$^+$   | $B \rightarrow K X$(3872) $\rightarrow \pi^+ \pi^- J/\psi \gamma J/\psi, D\bar{D}^*$ | Belle, CDF, D0, BaBar Molecule?       |                                  |
| $X$(3915)     | 3914 ± 4  | 28$^{+12}_{-14}$ | ?$^+$  | $\gamma \gamma \rightarrow \omega J/\psi$ | Belle                                 |                                  |
| $Z$(3930)     | 3929 ± 5  | 29 ± 10        | 2$^+$   | $\gamma \gamma \rightarrow Z$(3940) $\rightarrow D\bar{D}$ | Belle                                 |                                  |
| $X$(3940)     | 3942 ± 9  | 37 ± 17        | 0$^+$   | $e^+e^- \rightarrow J/\psi X$(3940) $\rightarrow D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$) | Belle, BaBar $2^3 P_1(c\bar{c})$? |                                  |
| $Y$(3940)     | 3943 ± 17 | 87 ± 34        | ?$^+$   | $B \rightarrow K Y(3940) \rightarrow \omega J/\psi$ (not $D\bar{D}^*$) | Belle, BaBar $2^3 P_1(c\bar{c})$? |                                  |
| $Y$(4008)     | 4008$^{+82}_{-49}$ | 220$^{+97}_{-80}$ | 1$^-$   | $(e^+e^-)_{ISR} \rightarrow Y$(4008) $\rightarrow \pi^+ \pi^- J/\psi$ | Belle, CLEO, Belle Hybrid?            |                                  |
| $Y$(4140)     | 4143 ± 3.1 | 11.7$^{+0.2}_{-0.1}$ | ?$^+$   | $B \rightarrow K Y(4140) \rightarrow J/\psi \phi$ | CDF                                   |                                  |
| $X$(4160)     | 4156 ± 29 | 139$^{+113}_{-65}$ | 0$^+$   | $e^+e^- \rightarrow J/\psi X$(4160) $\rightarrow D^*\bar{D}^*$ (not $D\bar{D}$) | Belle                                 |                                  |
| $Y$(4260)     | 4264 ± 12 | 83 ± 22        | 1$^-$   | $(e^+e^-)_{ISR} \rightarrow Y$(4260) $\rightarrow \pi^+ \pi^- J/\psi$ | BaBar, CLEO, Belle Hybrid?            |                                  |
| $Y$(4350)     | 4324 ± 24 | 172 ± 33       | 1$^-$   | $(e^+e^-)_{ISR} \rightarrow Y$(4350) $\rightarrow \pi^+ \pi^- J/\psi$ | BaBar                                 |                                  |
| $Y$(4360)     | 4361 ± 13 | 74 ± 18        | 1$^-$   | $(e^+e^-)_{ISR} \rightarrow Y$(4350) $\rightarrow \pi^+ \pi^- \psi$ | Belle                                 |                                  |
| $Y$(4630)     | 4634 ± 10.6 | 92$^{+41}_{-42}$ | 1$^-$   | $(e^+e^-)_{ISR} \rightarrow Y$(4630) $\rightarrow \Lambda^+_c \Lambda^-_c$ | Belle                                 |                                  |
| $Y$(4660)     | 4664 ± 12 | 48 ± 15        | 1$^-$   | $(e^+e^-)_{ISR} \rightarrow Y$(4660) $\rightarrow \pi^+ \pi^- \psi$ | Belle                                 |                                  |
| $Z_1$(4050)   | 4051$^{+24}_{-23}$ | 82$^{+51}_{-51}$ | ?$^+$   | $B \rightarrow K Z_1^+(4050) \rightarrow \pi^+ \chi_{c1}$ | Belle                                 |                                  |
| $Z_2$(4250)   | 4248$^{+185}_{-145}$ | 177$^{+320}_{-72}$ | ?$^+$   | $B \rightarrow K Z_2^+(4250) \rightarrow \pi^+ \chi_{c1}$ | Belle                                 |                                  |
| $Z$(4430)     | 4433 ± 1.5 | 45$^{+35}_{-35}$ | ?$^+$   | $B \rightarrow K Z_2^+(4430) \rightarrow \pi^+ \psi$ | Belle                                 |                                  |
| $Y_c$(10890)  | 10, 890 ± 3 | 55 ± 9         | 1$^-$   | $e^+e^- \rightarrow \gamma f_0 \rightarrow \pi^+ \pi^- \pi^0(1, 2, 3\pi)$ | Belle                                 |                                  |

An important mode to look for.

Rescattering via $D_s D_s^*$ Other possibilities are that the $Y(4140)$ is due to $D_s D_s^*$ rescattering \cite{28} or the opening up of a new final state channel \cite{29, 30}.

$D_s^+ D_s^{*-}$ Molecule The molecule explanation has been examined by a number of authors \cite{23, 27, 31, 32, 33, 34}. The $D_s^+ D_s^{*-}$ threshold is $\sim 4225$ MeV implying a binding energy of $\sim 80$ MeV. If one interprets the $Y(3940)$ to be a $D^+ D^*$ molecule the binding energy of the two systems are similar. Futhermore the decay $Y(4140) \rightarrow J/\psi \phi$ is similar to the decay $Y(3940) \rightarrow J/\psi \omega$ although the widths are different. The molecule picture predicts that decays proceed via rescattering with decays to hidden and open charm final states equally probable. One should search for decays to open modes like $D\bar{D}$ and $D\bar{D}^*$. Another prediction is that constituent mesons can decay independently so observation of decays such as $Y(4140) \rightarrow D_s^+ D_s^{*-} \gamma$ and $Y(4140) \rightarrow D_s^+ D_s^{*-} \gamma$ would provide evidence for the molecule picture \cite{27, 31, 33}. A $D^+ D_s^{-}$ molecule is also predicted with mass $\sim 4040$ MeV with $J/\psi \rho$ as a prominent final state to look for \cite{22}.

None of these explanations is compelling. A necessary first step to understand the $Y(4140)$ is to confirm it’s existence in another measurement as it has only been observed in one measurement at $3.8 \sigma$. It is then necessary to observe other decay modes to help to distinguish between the various possibilities.

5.2. The $X(3915)$

The $X(3915)$ is the most recent addition to the collection of $XYZ$ states (at least at the time of the conference). It was observed by Belle in $\gamma \gamma \rightarrow \omega J/\psi$ with a statistical significance of $7.5 \sigma$ \cite{4}. It has a measured mass and width of $M = 3914 \pm 3 \pm 2$ MeV and $\Gamma = 23 \pm 9^{+12}_{-13}$ MeV. These parameters are consistent with those of the $Y(3940)$. The $2\gamma$ widths $BR$ to $\omega J/\psi$ is $\Gamma_{\gamma \gamma} = B(X(3915) \rightarrow \omega J/\psi) = 69 \pm 16^{+21}_{-18}$ eV assuming $J^P = 0^+$ or $21 \pm 4^{+2}_{-2}$ eV for $J^P = 2^+$. For comparison $\Gamma_{\gamma \gamma} = B(Z(3930)) = 180 \pm 50 \pm 30$ eV.

5.3. The $Z^+(4430)$, $Z_1^+(4050)$ and $Z_2^+(4250)$ States

Belle observed a number of charmonium like states in $B$ decay that carry charge $2\bar{c}$, thus indicating that they cannot be conventional $c\bar{c}$ states. The first state to be discovered was the $Z^+(4430)$. The $\pi^+(2S)$ invariant mass distribution is shown in Fig. 7. The observed peak has a statistical significance of $6.5 \sigma$. It’s measured properties are $M = 4433 \pm 4 \pm 2$ MeV, $\Gamma = 45^{+18}_{-12} -13$ MeV, and $B(B^0 \rightarrow K^+ Z^+) \times B(Z^+ \rightarrow$...
The fits.)

\[ \pi \pm \psi' = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5} \]

The unusual properties of the \( Z^+ (4430) \) led to the usual explanations:

- [cu][cd] Tetraquark
- \( D^+ D_1 (2420) \) Threshold effect
- \( D^* D_1 (2420) \) \( J^P = 0^- \), 1^- Molecule \[ \psi (4430) \] resonance.

The molecule explanation predicts that the \( Z^+ (4430) \) will decay into \( D^* D^+ \pi \) and that it decays into \( \psi (2S) \pi \) via rescattering.

The Belle \( Z^+ (4430) \) observation was followed by a search by the BaBar collaboration in \( B \rightarrow K \pi^+ \psi (2S) \) [39]. BaBar performed a detailed analysis of the \( K \pi^- \) system, corrected for efficiency, and included \( S, P, \) and \( D \) waves in their analysis. Fig. 8 shows the invariant mass distributions from Belle and Babar. While there appears to be an excess of events in the \( Z^+ (4430) \) region in the BaBar data, BaBar finds no conclusive evidence in their data for the \( Z^+ (4430) \).

More recently Belle performed a complete Dalitz analysis [40]. Belle confirms the \( Z^+ (4430) \) with \( M = 4443^{+15}_{-12}^{+12}_{-13} \) MeV and \( \Gamma = 109^{+86}_{-52} \) MeV. The width is larger than the original measurements but the uncertainties are large.

The Belle collaboration has also observed two resonance structures in \( \pi^+ \chi_{c1} \) mass distributions shown in Fig. 9 [41] with masses and widths of \( M_1 = 4051^{+14}_{-17} \) MeV, \( \Gamma_1 = 82^{+21}_{-17}^{+47}_{-22} \) MeV and \( M_2 = 4248^{+144}_{-29}^{+180}_{-35} \) MeV, \( \Gamma_2 = 177^{+54}_{-39}^{+316}_{-60} \) MeV.

Belle has now found evidence for three charged charmonium like objects. If confirmed they represent clear evidence for some sort of multiquark state, either a molecule or tetraquark. Confirmation is needed for all three of them.

5.4. The \( X (3872) \)

The \( X (3872) \) is probably the most robust of all the charmonium like objects. It was first observed by Belle as a peak in \( \pi^+ \pi^- J/\psi \) in \( B^+ \rightarrow K^+ \pi^+ \pi^- J/\psi \) [42]. It was subsequently confirmed by CDF [43], D0 [44].
and BaBar \cite{45}. The PDG \cite{22} values for its mass and width are $M = 3872.2 \pm 0.8$ MeV and $\Gamma = 3.0^{+2.1}_{-1.7}$ MeV. Unlike most other $XYZ$ states there is a fair amount known about the $X(3872)$ properties. The radiative transition $X(3872) \to \gamma J/\psi$ has been observed by Belle \cite{46} and by BaBar \cite{47} and more recently $X(3872) \to (2S)\gamma$ by BaBar \cite{48}. This implies that the $X(3872)$ has $C = +$. A study of angular distributions by Belle favours $J^{PC} = 1^{++}$ \cite{49} while a higher statistics study by CDF allows $J^{PC} = 1^{+}$ or $2^{+}$ \cite{50}. In the decay $X(3872) \to \pi^{+}\pi^{-} J/\psi$ the dipion invariant mass is consistent with originating from $\rho \to \pi^{+}\pi^{-}$ \cite{51}. The decay $c\bar{c} \to \rho J/\psi$ violates isospin and should be strongly suppressed. The decay $X(3872) \to D^{0\bar{D}}\pi^{0}$ has been seen by Belle \cite{52} and the decay $X(3872) \to D^{0\bar{D}}\gamma$ by BaBar \cite{53}. These decays imply that the $X(3872)$ decays predominantly via $D^{0\bar{D}}$. To understand the nature of the $X(3872)$ we work through the now familiar possibilities and compare the theoretical predictions for each case to the $X(3872)$ properties.

5.4.1. Conventional Charmonium

These possibilities were discussed in Ref. \cite{54, 55, 56, 57}. The $1^{1}D_{2}$ and the $2^{3}P_{1}$ are the only conventional states with the correct quantum numbers that are close enough in mass to be associated with the $X(3872)$. However, both these possibilities have problems. Another new state, the $Z(3921)$, is identified with the $2^{3}P_{1}$ state implying that the $2P$ mass is $\sim 3940$ MeV. Identifying the $X(3872)$ with the $2^{3}P_{1}$ implies a spin splitting much larger than would be expected. If the $X$ were the $1^{1}D_{2}(c\bar{c})$, the radiative transition $1^{1}D_{2} \to \gamma 1^{3}S_{1}$ would be a highly suppressed $M2$ transition so that the observation of $X(3872) \to \gamma J/\psi$ disfavours identifying the $X(3872)$ as the $1^{1}D_{2}$ state.

5.4.2. Tetraquark

This possibility was proposed in Ref. \cite{53}. This scenario predicts more nearly degenerate states including charged states which have yet to be observed. A high statistics study by CDF of the $X(3872)$ mass and width tested the hypothesis of two states and finds $\Delta m < 3.6(95\% C.L.)$ with $M = 3871.61 \pm 0.16 \pm 0.19$ MeV \cite{50}. The mass splitting of the $X(3872)$ states produced in charged and neutral $B$ decays is consistent with zero. These measurements disfavour the tetraquark interpretation.

5.4.3. $D^{0}\bar{D}^{*0}$ Molecule

The molecule explanation appears to be the most likely interpretation of the $X(3872)$ \cite{50, 51, 52, 53}. It is very close to the $D^{0}\bar{D}^{*0}$ threshold so it is quite reasonable that it is an $S$-wave bound state. One of the early predictions of the molecule interpretation is that \cite{62}:

$$\Gamma(X(3872) \to \rho J/\psi) \simeq \Gamma(X(3872) \to \omega J/\psi) \quad (8)$$

so that large isospin violations are expected. On the other hand, the decays $X(3872) \to \gamma J/\psi$ and $X(3872) \to \gamma(2S)$ \cite{18} indicate it has $c\bar{c}$ content. The most likely explanation is that both the $X(3872)$ and $Y(3940)$ have more complicated structure, consisting of mixing with both $2^{3}P_{1}(c\bar{c})$ and $D^{0}\bar{D}^{*0}$ components \cite{64, 65, 66, 67, 68}. This may also explain the unexpected large partial width for $Y(3940) \to J/\psi \omega$ \cite{69}.

5.5. $Y$ States in ISR ($J^{PC} = 1^{--}$)

There are now six “$Y$” states seen in $e^{+}\bar{e}^{-} \to \gamma_{ISR} J/\psi$. Because they are seen in ISR they have $J^{PC} = 1^{--}$. Because of time and space constraints I will only discuss two of these states; the $Y(4630)$ observed by Belle \cite{70} which is one of the newest $Y$ states and the $Y(4260)$ first observed by BaBar \cite{71} which is one of the oldest.

5.5.1. $Y(4630)$

The $Y(4630)$ was seen by the Belle collaboration in $e^{+}\bar{e}^{-} \to \Lambda_{c}^{+}\Lambda_{c}^{-}\gamma_{ISR}$ with mass $M = 4634_{-7-8}^{+8+5}$ MeV and $\Gamma = 92_{-24-21}^{+40+10}$ MeV. The $\Lambda_{c}^{+}\Lambda_{c}^{-}$ mass distribution is shown in Fig10. There are some speculations about what it might be. A possible explanation is that it is a dibaryon threshold effect. A similar effect is also seen by Belle in $B \to \Lambda_{c}^{+}\bar{p}\pi^{-}$ \cite{72} with a 6.2σ peak observed at threshold in the $\Lambda_{c}^{+}\bar{p}$ invariant mass distribution. Other possibilities put forward are to identify the the $Y(4630)$ with the $Y(4660)$, also observed in ISR, but in the $\pi^{+}\pi^{-}\omega$ final state, or to identify the $Y(4630)$ with the 5$^{4}S_{1}$ charmonium state.

5.5.2. $Y(4260)$

The $Y(4260)$ was the first of the $Y$ states to be observed. It was first observed by the BaBar collaboration as an enhancement in the $\pi\pi J/\psi$ final state in $e^{+}\bar{e}^{-} \to \gamma_{ISR} J/\psi \pi\pi$ \cite{71}. The $\pi^{+}\pi^{-} J/\psi$ invariant mass distribution is shown in Fig11 \cite{71}. BaBar found further evidence for the $Y(4260)$ in $B \to K(\pi^{+}\pi^{-} J/\psi)$ \cite{73} and it was also independently confirmed by CLEO \cite{74} and Belle \cite{75}. Thus, it is the oldest and most robust of the $Y$ states. The possibilities for the $Y(4260)$ are:

Conventional Charmonium

The first unaccounted $1^{--}$ state is the $\psi(3D)$ with predicted mass $M[\psi(3D)] \sim 4500$ MeV which is much heavier than the observed mass. Thus, the $Y(4260)$ appears to represent an overpopulation of the expected $1^{--}$ states. In addition, the absence of open charm production speaks against it being a conventional $c\bar{c}$ state. There was the suggestion that the $Y(4260)$ could be identified as the $\psi(4S)$ state \cite{70}, displacing the $\psi(4415)$ from that slot although the authors acknowledge this fit is somewhat forced.
Tetraquark Maiani et al. proposed that the \( Y(4260) \) is the first radial excitation of the \([c\bar{c}]\bar{c}\bar{s}\). They predict that the \( Y(4260) \) should decay predominantly to \( D_s \bar{D}_s \) and predict a full nonet of related four-quark states.

\( D_1 D^* \) Bound State Close and Downum suggest that two \( S \)-wave mesons can be bound via pion exchange leading to a spectroscopy of quasi-molecular states above 4 GeV and a possible explanation of the \( Y(4260) \) and \( Y(4360) \). They suggest searches in \( DD\pi \) channels as well as in \( B \) decays.

\( c\bar{c} \) Hybrid This has been suggested in a number of papers. This possibility has a number of attractive features. The flux tube model \( S \) and lattice QCD \( S \) predict the lowest \( c\bar{c} \) hybrid at \( \sim 4200 \text{ MeV} \). LGT suggests searching for other closed charm models with \( J^{PC} = 1^{−−} \) such as \( J/\psi \eta \), \( J/\psi \eta' \), \( \chi_{cJ} \omega \), etc. Most models predict that the lowest mass hybrid mesons will decay to \( S + P \)-wave mesons final states. The dominant decay mode is expected to be \( D^+ D_1(2420) \). The \( D_1(2420) \) has a width of \( \sim 300 \text{ MeV} \) to \( D^0 \pi \) which suggests to search for the \( Y(4260) \) in \( DD^* \pi \) final states. Evidence of a large \( DD_1(2420) \) signal would be strong evidence for the hybrid interpretation. Note that searches for these decays by Belle find no evidence. Another prediction of the hybrid explanation is to search for partner states. The flux tube model predicts a multiplet of states nearby in mass with conventional quantum numbers: \( 0^{−−}, 1^{−−}, 2^{−−}, 1^{++}, 1^{−−} \) and states with exotic quantum numbers \( 0^{++}, 1^{−+}, 2^{++} \). Identifying some of these \( J^{PC} \) partners would further validate the hybrid scenario.

5.5.3. \( Y \) States in ISR: What are they?

There are now six \( Y \) states observed in ISR. I’ve described the possibilities for the \( Y(4260) \) but the same process of elimination follows for all of them. The measured \( Y \) masses don’t match the peaks in the \( D^{(*)} D^{(*)} \) cross sections and there does not appear to be room for additional conventional \( c\bar{c} \) states in this mass region unless the predictions are way off. It has been suggested that many of the \( Y \)-states are multiquark states, either tetraquarks or molecules. Molecules are generally believed to lie just below threshold and are bound via \( S \)-wave scattering and pion exchange. Few of the \( Y \)-states lie close to thresholds so at best this might explain special cases but cannot be a general explanation. Other problems with the multiquark explanation are discussed below. The final possibility considered is that some of the \( Y \) states are charmonium hybrids. The \( Y(4260) \) is the most robust of all these states and is quite possibly a hybrid. Most of the \( Y \)-states, however, need confirmation and more detailed measurements of their properties.
6. Summary

During the past year there have been many new developments in hadron spectroscopy. In some cases the new results reinforce our understanding in the context of the constituent quark model while in other cases they demonstrate that we still have much to learn.

Many hadrons with heavy quarks have been observed and their properties are in good agreement with theory. The observation of the $\eta_b$ by BaBar in the electromagnetic transitions $\Upsilon(3S) \rightarrow \gamma \eta_b$ and $\Upsilon(2S) \rightarrow \gamma \eta_b$ provides further evidence that QCD motivated quark models and Lattice QCD calculations are essentially correct. Likewise, the properties of the ground state baryons with $b$ quarks are well described by the simplest of quark model assumptions to the point that they can be used as a homework problem in a particle physics course.

In contrast, it is not at all clear what most of the new charmonium-like $XYZ$ states are. There are now something like 16 charmonium like $XYZ$ states with new ones, seemingly, discovered every other day. A few can be identified as conventional states and a few more, the $X(3872)$ and $Y(4260)$ for example, are strong candidates for hadronic molecule and hybrid states. These latter two are the best understood, having been confirmed by several experiments and observed in different processes and channels.

It has been suggested that many of the $XYZ$ states are multiquark states, either tetraquarks or molecules. The problem with the tetraquark explanation is that it predicts multiplets with other charge states that have not been observed, and larger widths than have been observed. The possibility that some of the $XYZ$ states are molecules is likely intertwined with threshold effects that occur when channels are opened up. Including coupled-channel effects and the rescattering of charmed meson pairs in the mix can also result in shifts of the masses of $c\bar{c}$ states and result in meson-meson binding which could help explain the observed spectrum $65, 72, 88, 94$. In my view, a comprehensive study including coupled channels is a necessity if we are to understand the charmonium spectrum above $D\bar{D}$ threshold.

Many of the $XYZ$ states need independent confirmation and to understand them will require detailed studies of their properties. With better experimental and theoretical understanding of these states we will have more confidence in believing that any of these new states are non-conventional $c\bar{c}$ states like molecules, tetraquarks, and hybrids.

Hadron spectroscopy continues to intrigue with a bright future. There is the potential for many new measurements; BaBar has considerable unanalyzed data that might hold evidence for new states, Belle and BESIII have bright futures, and JLab, PANDA, and the LHC promise to produce exciting new physics in the longer term.

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