NEW CHARMONIUM-LIKE STATES

Adapted from EICHTEN 07 in May 2008 by S. Eidelman, H. Mahlke-Krüger, and C. Patrignani.

Many new charmonium states above $D\overline{D}$ threshold have recently been observed. While some of these states appear to be consistent with conventional $c\bar{c}$ states, others do not. Here we give a brief survey of the new states and their possible interpretations. In many cases, the picture is not entirely clear. This situation could be remedied by a coherent search of the decay pattern to $D\bar{D}^{(*)}$, search for production in two-photon collisions and initial state radiation (ISR), the study of radiative decays of charmonia, analysis of angular distributions to determine quantum numbers, and of course, by improved statistical precision of the current measurements. The uncertainty in the interpretation for these states is reflected in the arbitrariness of the nomenclature used in the literature. In this review, we refer to them as to $X(m)$, following the standard naming convention for states of uncertain assignment. Note that some of the states discussed below are not yet in the regular listings because they are observed by a single experiment only,

1. $X(3872)$

The $X(3872)$, discovered by Belle in B decays [1] and confirmed by BaBar [2] and in hadronic production by CDF [3] and D0 [4], is a narrow state of mass 3872 MeV/c^2 that was first seen decaying to $J/\psi\pi^+\pi^-$. No signal at this mass was seen in $B \to X^- K$, $X^- \to \pi^-\pi^0 J/\psi$ [5], which would have implied a charged partner of $X(3872)$. It was not observed in two-photon production or initial state radiation [6]. Subsequent studies focused on determining the mass, width, and decay properties in order to establish its quantum numbers and possible position in the charmonium system of states. To date, decays to $\pi^+\pi^- J/\psi$, $\gamma J/\psi$, $D^0\bar{D}^0\pi^0$, and possibly $\pi^+\pi^-\pi^0 J/\psi$ have been reported.

The averaged mass of this state is $M = 3872.2 \pm 0.8$ MeV/c^2 [7]; the width is determined to be below detector resolution, $\Gamma < 2.3$ MeV (90% C.L.) [1] in $J/\psi\pi^+\pi^-$ decays and $3.0^{+1.9}_{-1.4} \pm 0.9$ MeV [8] in $\bar{D}^{*0}D^0$ decays.

The combined branching fraction product from Belle and BaBar is $\mathcal{B}[B^+ \to K^+X(3872)] \times \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] = (11.4 \pm 2.0) \times 10^{-6}$ [9]. After setting a limit of $\mathcal{B}[B^+ \to K^+X(3872)] < 3.2 \times 10^{-4}$ (90% C.L.), BaBar [10] derives $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] > 4.2\%$ (90% C.L.). We can compare this with other states above open flavor threshold: $\mathcal{B}[\psi(3770) \to \pi^+\pi^- J/\psi] = (1.93 \pm 0.28) \times 10^{-3}$ [9] (partial width 46 keV) and limits $\mathcal{B}[\psi(4040,\ 4160) \to \pi^+\pi^- J/\psi]$ of order 10^{-3} [7] (partial widths $\sim 100\,\text{keV}$).

Regular charmonium states that cannot decay to D pairs are also expected to have a narrow width; however, in these cases, E1 transitions to the χ_{cJ} states are preferred. This is not seen in the data for $X(3872)$ [1]. This result also disfavors its interpretation as a $1^{1,3}D_2$ state.

Decay into a pair of D mesons has not been observed, and upper limits on the rate are in the range of a few times that for $\pi^+\pi^- J/\psi$ [11]. A signal in $B \to (D^0\bar{D}^0\pi^0)K$ with $m(D^0\bar{D}^0\pi^0)$ observed by Belle in the right range is the first candidate for open-charm decays of $X(3872)$ [12], confirmed by BaBar in Ref. 8.BaBar also observes $X(3872) \to D^0\bar{D}^0\gamma$. The relative rate of $D^0\bar{D}^0\pi^0$ and $D^0\bar{D}^0\gamma$ supports the hypothesis that the $X(3872)$ predominantly decays to $D^0\bar{D}^{*0}$. The observed rate is an order of magnitude above that for $\pi^+\pi^- J/\psi$.

The dipion mass distribution favors high $m(\pi^+\pi^-)$ values. This is not untypical for charmonium states (*cf.* $\psi(2S) \to \pi^+\pi^- J/\psi$), but could be an indication that the pion pair might even be produced in a ρ configuration; if that were indeed the case the $X(3872)$ could not be a charmonium state. A search for $X(3872) \to \pi^0\pi^0 J/\psi$ would be most helpful to clarify this aspect (as well as to determine the $\pi^0\pi^0 J/\psi : \pi^+\pi^- J/\psi$ ratio) because the decay chain $X(3872) \to \rho^0 J/\psi \to \pi^0\pi^0 J/\psi$ would be forbidden. Observation of $X(3872) \to \pi^0\pi^0 J/\psi$ would therefore rule out the hypothesis of an intermediate ρ state. The decay $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ was observed at a rate comparable to that of $\pi^+\pi^- J/\psi$ [13]. The $m(\pi^+\pi^-\pi^0)$ distribution is concentrated at the highest values, coinciding with the kinematic limit, which prompted speculations that the decay might proceed through (the low-side tail of) an ω.

Since the $X(3872)$ lies well above $D\overline{D}$ threshold but is narrower than experimental resolution, unnatural $J^P = 0^-, 1^+, 2^-$ is favored. An angular distribution analysis by the Belle collaboration, utilizing in part suggestions in Ref. 14, favors $J^{PC} = 1^{++}$ [15], although a higher-statistics analysis by CDF cannot distinguish between $J^{PC} = 1^{++}$ or 2^{-+} [16] (see also [17–19]) . $J^{PC} = 2^{-+}$ is disfavored by the observation of the $D^0\overline{D}^0\pi^0$ decay mode [8,12], which would require at least two units of relative orbital angular momentum in the three-body state, very near threshold. On the other hand, it has been argued [20] that $J^{PC} = 2^{-+}$ could more naturally explain the observed mass shift between the $\pi^+\pi^- J/\psi$ and the $D^0\overline{D}^{*0}$ modes.

Of conventional $c\bar{c}$ states, only the $1D$ and $2P$ multiplets are nearby in mass. Taking into account the angular distribution analysis, only the $J^{PC} = 1^{++}$ 2^3P_1 and 2^{-+} 1^1D_2 assignments are possible. The decay $X(3872) \to \gamma J/\psi$ is observed at a rate about a quarter or less of that for the $X(3872) \to \pi^+\pi^- J/\psi$ [13,21], and implies $C = +$. This would be an E1 transition for 2^3P_1, but a more suppressed higher multipole for 2^{-+}, and therefore the $J^{PC} = 1^{++}$ interpretation, appears more likely assuming $c\bar{c}$ content. For a 1^{++} state, the only surviving candidate is the 2^3P_1. However, an identification of the $Z(3931)$ with the 2^3P_2 implies a 2^3P_2 mass of ~ 3930 MeV/c^2, which is inconsistent with the 2^3P_1 interpretation of the $X(3872)$ if the $2^3P_2 - 2^3P_1$ mass splittings are decidedly lower than 50 MeV/c^2 [22,23]. This favors the conclusion that the $X(3872)$ may be a $D^0\overline{D}^{0*}$ molecule or "tetraquark" [24] state. It has many features in common with an S-wave bound state of $(D^0\overline{D}^{*0} + \overline{D}^0 D^{*0})/\sqrt{2} \sim c\bar{c}u\bar{u}$ with $J^{PC} = 1^{++}$ [25]. Its simultaneous decay to $\rho J/\psi$ and $\omega J/\psi$ with roughly equal branching ratios is a consequence of this "molecular" assignment. The upper limit on $X(3872) \to \eta J/\psi$ [26] is consistent with expectations for a charmonium state, as well as a hybrid. A new measurement of $M(D^0) = 1864.847 \pm 0.150 \pm 0.095$ MeV/c^2 [27] implies $M(D^0\overline{D^{*0}}) = 3871.81 \pm 0.36$ MeV/c^2, and hence a binding energy of 0.6 ± 0.6 MeV.

2. $X(3930)$ (or $Z(3930)$) : a $\chi_{c2}(2P)$ candidate

Belle has reported a candidate for a $2^3P_2(\chi_{c2}(2P))$ state in $\gamma\gamma$ collisions [28], decaying to $D\overline{D}$. The state appears as an enhancement in the $m(D\overline{D})$ distribution at a statistical significance of 5.3σ. The relative D^+D^- and $D^0\overline{D}^0$ rates are consistent with expectations based on isospin invariance and the $D^+ - D^0$ mass difference. A fit combining charged and neutral modes yields mass and width $M = 3929 \pm 5 \pm 2$ MeV/c^2 and $\Gamma = 29 \pm 10 \pm 2$ MeV. Although in principle the D-pair could be produced from $D^*\overline{D}$, the observed transverse momentum spectrum of the $D\overline{D}$ pair is consistent with no contribution from $D^*\overline{D}$.

The $X(3930)$ interpretation as $\eta_c(3S)$ is ruled out by the observation of its decay to $D\overline{D}$. Both $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$ are expected to decay to $D\overline{D}$ (however, $\chi_{c1}(2P)$ only decays to $D^*\overline{D}$). To distinguish between the two remaining hypotheses, the distribution in θ^*, which is the angle of the D-meson relative to the beam axis in the $\gamma\gamma$ center-of-mass frame, is examined. This distribution is consistent with $\sin^4\theta^*$ as expected for a state with $J = 2, \lambda = \pm 2$. The two-photon width is, under the assumption of a tensor state, measured to be $\Gamma_{\gamma\gamma} \cdot \mathcal{B}_{D\overline{D}} = 0.18 \pm 0.05 \pm 0.03$ keV.

BaBar has searched for $X(3930)$ decay into $\gamma J/\psi$ [21], and set an upper limit $\mathcal{B}(B \to X(3930) + K) \times \mathcal{B}(X(3930) \to \gamma J/\psi) < 2.5 \times 10^{-6}$.

The predicted mass of the $\chi_{c2}(2P)$ is 3972 MeV/c^2 and the predicted partial widths and total width assuming $M[2^3P_2(c\overline{c})] = 3930$ MeV/c^2 are [22,29]

$$\Gamma(\chi_{c2}(2P) \to D\overline{D}) = 21.5 \ \text{MeV},$$

$$\Gamma(\chi_{c2}(2P) \to D\overline{D}^*) = 7.1 \ \text{MeV and}$$

$$\Gamma_{\text{total}}(\chi_{c2}(2P)) = 28.6 \ \text{MeV},$$

in good agreement with the experimental measurement. Furthermore, using $\Gamma(\chi_{c2}(2P) \to \gamma\gamma) = 0.67$ keV [30] $\times\mathcal{B}(\chi_{c2}(2P) \to D\overline{D}) = 70\%$ implies $\Gamma_{\gamma\gamma} \cdot \mathcal{B}_{D\overline{D}} = 0.47$ keV, which is within a factor of 2 of the observed number, fairly good agreement considering the typical reliability of two-photon partial width predictions.

The observed $X(3930)$ properties are consistent with those predicted for the $\chi_{c2}(2P)$ $2^3P_2(c\overline{c})$ state. So far, the only mild surprise is the observed mass, which is $40-50\,\mathrm{MeV}/c^2$ below expectations. Adjusting that, all other properties observed so far can probably be accomodated within the framework of [22,29]. The $\chi_{c2}(2P)$ interpretation could be confirmed by observation of the $D\overline{D}^*$ final state. We also note that the $\chi_{c2}(2P)$ is predicted to undergo radiative transitions to $\psi(2S)$ with a partial width of $\mathcal{O}(100\,\mathrm{keV})$ [22,23]. Needs confirmation.

3. *X*(3940)

Belle studied double-charmonium production and $e^+e^- \to J/\psi + X$ near the $\Upsilon(4S)$ [31], and observed enhancements for the well-known charmonium states η_c, χ_{c0}, and $\eta_c(2S)$ at rates and masses consistent with other determinations. In addition, a peak at a higher energy was found. The mass and width were measured to be $M = 3936 \pm 14 \pm 6$ MeV/c^2 and $\Gamma = 39 \pm 26$ (stat) MeV.

To further examine the properties of this enhancement, Belle searched for exclusive decays $J/\psi \to D\overline{D}^{(*)}$, given that these decays are kinematically accessible. An enhancement at the $X(3940)$ mass is seen for $D\overline{D}^*$, but not for $D\overline{D}$. The mass and width determined in this study are $M = (3943 \pm 6 \pm 6)\,\mathrm{MeV}/c^2$, $\Gamma < 52\,\mathrm{MeV}$ (90% C.L.). Note that the inclusive and exclusive samples have some overlap, and thus the two mass measurements are not statistically independent. The overlap has been eliminated for the branching fraction determination. A signal of 5.0σ significance was seen for $D\overline{D}^*$, but none for $D\overline{D}$. In addition, the $X(3940)$ did not show a signal for a decay $\omega J/\psi$, unlike the $Y(3940)$.

If confirmed, the decay to $D\overline{D}^*$ but not $D\overline{D}$ suggests the $X(3940)$ has unnatural parity. The lower masses η_c and η_c' are also produced in double-charm production. One is therefore led to try an η_c'' assignment, although this state is expected to have a somewhat higher mass [23]. The predicted width for a 3^1S_0 state with a mass of 3943 MeV/c^2 is ~ 50 MeV [22], which is in not in conflict with the obtained upper limit for the $X(3940)$ width.

Another possibility due to the dominant $D\overline{D}^*$ final states is that the $X(3940)$ is the $2^3P_1(c\bar{c})$ χ_1' state. It is natural to consider the $2P(c\bar{c})$, since the 2^3P_J states are predicted to lie in the 3920–3980 MeV/c^2 mass region, and the widths are predicted to be in the range $\Gamma(2^3P_J) = 30$–165 MeV [23]. The dominant $D\overline{D}^*$ mode would then suggest that the $X(3940)$ is the $2^3P_1(c\bar{c})$ state. The problems with this interpretation are (1) there is no evidence for the $1^3P_1(c\bar{c})$ state in the same data, (2) the predicted width of the $2^3P_1(c\bar{c})$ is 140 MeV (assuming $M(2^3P_1(c\bar{c})) = 3943$ MeV/c^2) [32], and (3) there is another candidate for the $1^3P_1(c\bar{c})$ state, the $X(3945)$ (or $Y(3940)$).

A possible interpretation of the $X(3940)$ is that it is the $3^1S_0(c\bar{c})$ η_c'' state. Tests of this assignment are to study the angular distribution of the $D\overline{D}^*$ final state and to observe it in $\gamma\gamma \to D\overline{D}^*$.

Further analysis of Belle confirms the $X(3940)$ and reports a new state $X(4160)$ [33].

4. $X(3945)$ (or $Y(3940)$)

The $X(3945)$ is seen by Belle in the $\omega J/\psi$ subsystem in the decay $B \to K\omega(\to \pi^+\pi^-\pi^0)J/\psi$ [34]. The final state is selected by kinematic constraints that incorporate the parent particle mass $m(B)$ and the fact that the B-meson pair is produced with no additional particles. Background from decays such as $K_1(1270) \to \omega K$ is reduced by requiring $m(\omega J/\psi) >$ 1.6 GeV. The $K\omega J/\psi$ final state yield is then further examined in bins of $m(\omega J/\psi)$. A threshold enhancement is observed, which is fit with a threshold function suitable for phase-space production of this final state and an S-wave Breit-Wigner shape. The reported mass and width of the enhancement are $M = 3943 \pm 11 \pm 13$ MeV/c^2 and $\Gamma = 87 \pm 22 \pm 26$ MeV. A fit without a resonance contribution gives no good description of the data. The state has been recently confirmed in the same process by BaBar [35]: the mass and width, $M = 3914.6^{+3.8}_{-3.4} \pm 1.9$ MeV/c^2 and $\Gamma = 34^{+12}_{-8} \pm 5$ MeV, are somewhat smaller than the values reported by Belle, but are not incompatible with them. The average mass and width values are $M = 3916 \pm 7$ MeV/c^2 (s=1.6) and $\Gamma = 41 \pm 18$ MeV (s=1.5).

The mass and width of the $X(3945)$ suggest a radially excited P-wave charmonium state. Belle has measured a combined branching ratio of $\mathcal{B}(B \to KX) \cdot \mathcal{B}(X \to \omega J/\psi) = (7.1{\pm}1.3{\pm}3.1){\times}10^{-5}$. BaBar measures $\mathcal{B}(B^+ \to K^+X){\cdot}\mathcal{B}(X \to \omega J/\psi) = (4.9^{+1.0}_{-0.9} \pm 0.5) \times 10^{-5}$, $\mathcal{B}(B^0 \to K^0X) \cdot \mathcal{B}(X \to \omega J/\psi) = (1.3^{+1.3}_{-1.1} \pm 0.2) \times 10^{-5}$, with a ratio $\mathcal{B}(B^0 \to K^0X) : \mathcal{B}(B^+ \to K^+X) = 0.27^{+0.28}_{-0.23}{}^{+0.04}_{-0.01}$ One expects that $\mathcal{B}(B \to K\chi_{cJ}(2P)) < \mathcal{B}(B \to K\chi_{cJ}) = 4 \times 10^{-4}$. This implies that $\mathcal{B}(X(3945) \to \omega J/\psi) > 12\%$, which is unusual for a $c\bar{c}$ state above open-charm threshold.

For the $\chi_{c1}(2P)$ $2^3P_1(c\bar{c})$, we expect $D\overline{D}^*$ to be the dominant decay mode with a predicted width of 140 MeV [32], which is not inconsistent with that of the $X(3945)$ within the theoretical and experimental uncertainties. The mass of the $\chi_{c1}(2P)$ state is expected to be smaller than the mass of the $\chi_{c2}(2P)$. If we identify the $\chi_{c2}(2P)$ with the state observed by Belle in $\gamma\gamma \to D\overline{D}$, the smaller mass value measured by BaBar would be consistent with the assignment of the $X(3945)$ as the $\chi_{c1}(2P)$ state. Furthermore, the χ_{c1} is also seen in B-decays. Although the decay $1^{++} \to \omega J/\psi$ is unusual, the corresponding decay $\chi_{b1}(2P) \to \omega \Upsilon(1S)$ has also been seen [36]. One possible explanation for this unusual decay mode is that rescattering through $D\overline{D}^*$ is responsible: $1^{++} \to D\overline{D}^* \to \omega J/\psi$. Another contributing factor might be mixing with the possible molecular state tentatively identified with the $X(3872)$.

BaBar has searched for the $X(3945)$ decay into $\gamma J/\psi$ [21], and set an upper limit $\mathcal{B}(B \to X(3945) + K) \times \mathcal{B}(X(3945) \to \gamma J/\psi) < 1.4 \times 10^{-5}$.

The $\chi_{c1}(2P)$ assignment can be tested by searching for the $D\overline{D}$ and $D\overline{D}^*$ final states, and by studying their angular distributions. With the present experimental data, a $\chi_{c1}(2P)$ assignment cannot be ruled out.

5. $X(4260)$ (or $Y(4260)$) and further states in $\pi^+\pi^-J/\psi$

Perhaps the most intriguing of the recently discovered states is the $X(4260)$ reported by BaBar as an enhancement in the $\pi^+\pi^-J/\psi$ subsystem in the radiative return reaction $e^+e^- \to \gamma_{\rm ISR}J/\psi\pi^+\pi^-$ [37]. This state was subsequently confirmed in radiative return by CLEO [38] and Belle [39]. Further evidence was seen by BaBar in $B \to K(\pi^+\pi^-J/\psi)$ [40].

The CLEO Collaboration has also confirmed the $X(4260)$ in a direct scan [41]. There are also weak signals for $\psi(4160) \to \pi^+\pi^-J/\psi$ (3.6σ) and $\pi^0\pi^0J/\psi$ (2.6σ), consistent with the $X(4260)$ tail, and for $\psi(4040) \to \pi^+\pi^-J/\psi$ (3.3σ). In addition to a clear enhancement around 4.25 GeV/c^2, the $\pi^+\pi^-J/\psi$ invariant mass distribution observed by Belle also exhibits a clustering of events around 4.05 GeV/c^2, which is significantly above the background level. If they use the same functional form as BaBar (a single Breit-Wigner resonance plus an incoherent second-order polynomial background), they find parameters of the $X(4260)$ consistent with BaBar. If a second resonance is added, the quality of the fit improves significantly. Assuming that there are two resonances described by Breit-Wigner amplitudes, Belle performs another fit and obtains parameters of these structures [39]. Both structures are significant: for example, the one at 4.05 GeV/c^2 has a significance of 7.4σ. In a case of relatively low statistics and constant width (no energy dependence), such a fit has two equally good solutions (exactly the same fit quality) with equal mass and width, but notably different partial widths to e^+e^-, and the relative phase between the two structures. The masses and widths are reported as $M(R1) = 4008 \pm 40^{+114}_{-28}$ MeV/c^2, $\Gamma(R1) = 226 \pm 44 \pm 87$ MeV, $M(R2) = 4247 \pm 12^{+17}_{-32}$ MeV/c^2, $\Gamma(R1) = 108 \pm 19 \pm 10$ MeV. The coupling is consistent with the other measurements for solution I for the partial width. Solution II, though equally valid, leads to a value $B(X \to \pi^+\pi^-J/\psi) \times \Gamma_{e^+e^-}$ substantially higher.

The overall pattern is not similar to BaBar [37], where a two-resonance fit gave a lower structure with mass close to 4260 MeV/c^2, and a width of 50 MeV along with a narrow one at 4330 MeV/c^2, with no significant improvement of the fit quality. (The single-resonance baseline fit resulted in $M = 4259 \pm 8^{+2}_{-6}$ MeV$/c^2$, $\Gamma = 88 \pm 23^{+6}_{-4}$ MeV; adding the $\psi(4040)$, $\psi(4160)$, or $\psi(4415)$ did not help.)

Mass and width of the higher structure measured by Belle are consistent with those of the $X(4260)$ observed by BaBar [37] and CLEO [38]. Although the mass of the first resonance is close to that of the $\psi(4040)$, the fitted width is much higher than the world average one (80 ± 10 MeV). The mass of the second resonance is higher than that of the $\psi(4160)$. Therefore, these structures should be considered as new states rather than confirmation of the existing ψ' states. Of course, interpretation of these enhancements as new resonances is not at all unambiguous; they are close to $D^{(*)}\overline{D}^{(*)}$ thresholds, where coupled-channel effects and rescattering may strongly affect the cross section.

A variety of channels have been searched for now [41–45], of which $\pi^0\pi^0 J/\psi$ and $K^+K^- J/\psi$ only have been observed [41,46]. The ratios between the branching fractions of different channels should help narrow down the possible explanations of $X(4260)$. For example, the upper limit for the ratio of $D\overline{D}$ to $\pi^+\pi^- J/\psi$ of 1.0 at 90% C.L. [43] may not seem particularly tight at first glance, but is to be compared, for example, with the same ratio for the $\psi(3770)$, where it is about 500.

A number of explanations have appeared in the literature: $\psi(4S)$ [47], $cs\overline{cs}$ tetraquark [48], and $c\overline{c}$ hybrid [49–52]. In some models, the mass of the $X(4260)$ is consistent with the $4S(c\overline{c})$ level [47]. Indeed, a $4S$ charmonium level at 4260 MeV$/c^2$ was anticipated on exactly this basis [53]. With this assignment, the nS levels of charmonium and bottomonium are remarkably congruent to one another. However, other calculations using a linear plus Coulomb potential identify the $4^3S_1(c\overline{c})$ level with the $\psi(4415)$ state (*e.g.*, Ref. 23). If this is the case the first unaccounted-for $1^{--}(c\overline{c})$ state is the $\psi(3^3D_1)$. Quark models estimate its mass to be $M(3^3D_1) \simeq 4500$ MeV$/c^2$, which is much too heavy to be the $X(4260)$. The $X(4260)$ therefore represents an overpopulation of the expected 1^{--} states. The absence of open-charm production also argues against it being a conventional $c\overline{c}$ state.

The hybrid interpretation of $X(4260)$ is appealing. The flux-tube model predicts that the lowest $c\overline{c}$ hybrid mass is ~ 4200 MeV/c^2 [54] with lattice-gauge theory having similar expectations [55]. Models of hybrids typically expect the wave function at the origin to vanish, implying a small e^+e^- width in agreement with the observed value. Lattice-gauge theory found that the $b\overline{b}$ hybrids have large couplings to closed-flavor channels [56]. The proposed scenario resembles the situation in charmonium, where the hybrid candidate $X(4260)$ shows a surprisingly large partial width $\Gamma(\pi^+\pi^- J/\psi)$ compared to its other decay modes. Moreover, $J/\psi\pi^+\pi^-$ production is much more prominent at the $X(4260)$ than at the conventional states $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$.

One predicted consequence of the hybrid hypothesis is that the dominant hybrid charmonium open-charm decay modes are expected to be a meson pair with an S-wave (D, D^*, D_s, D_s^*) and a P-wave (D_J, D_{sJ}) in the final state [50]. The dominant decay mode is expected to be $D\overline{D}_1$ + c.c.. Evidence for a large $D\overline{D}_1$ signal would be strong evidence for the hybrid interpretation. A complication is that $D\overline{D}_1$ threshold is 4287 MeV/c^2, if we consider the lightest D_1 to be the narrow state noted in Ref. 9 at 2422 MeV/c^2. The possibility also exists that the $Y(4260)$ could be a $D\overline{D}_1$ *bound state*. It would decay to $D\pi\overline{D}^*$, where the D and π are not in a D^*. Note that the dip in $R_{e^+e^-}$ occurs just below $D\overline{D}_1$ threshold, which may be the first S-wave meson pair accessible in $c\overline{c}$ fragmentation [50,57]. In addition to the hybrid decay modes given above, lattice-gauge theory suggests that we search for other closed-charm modes with $J^{PC} = 1^{--}$: $J/\psi\eta$, $J/\psi\eta'$, $\chi_{cJ}\omega$, and more. Distinguishing among the interpretations of the $X(4260)$ will likely require careful measurement of several decay modes.

If the $X(4260)$ is a hybrid, it is expected to be a member of a multiplet consisting of eight states with masses in the 4.0 to 4.5 GeV/c^2 mass range, with lattice-gauge theory preferring the higher end of the range [58]. It would be most convincing if some of these partners were found, especially the J^{PC} exotics. In the flux-tube model, the exotic states have $J^{PC} = 0^{+-}$, 1^{-+}, and 2^{+-}, while the non-exotic, low-lying hybrids have 0^{-+}, 1^{+-}, 2^{-+}, 1^{++}, and 1^{--}.

6. $X(4360)$ (or $Y(4360)$) and further states in $\pi^+\pi^-\psi(2S)$

In the radiative return process $e^+e^- \to \gamma + X$, BaBar [59] reports a broad structure decaying to $\pi^+\pi^-\psi(2S)$, where $\psi(2S) \to \pi^+\pi^- J/\psi$. A single-resonance hypothesis with $M(X) = (4324 \pm 24)$ MeV/c^2 and $\Gamma(X) = (172 \pm 33)$ MeV (errors are statistical only) is adequate to fit the observed mass spectrum. However, they cannot exclude that the structure observed is a manifestation of a new decay mode of the $X(4260)$.

Belle also studies this final state with a 2.2 times bigger statistics, and observes two distinct peaks in the $\pi^+\pi^-\psi(2S)$ invariant mass distribution, at 4.36 GeV/c^2 and 4.66 GeV/c^2 [60]. Assuming that there are two Breit-Wigner resonances, they obtain the parameters of the structures: $M(X1) = 4361 \pm 9 \pm 9$ MeV/c^2, $\Gamma(X1) = 74 \pm 15 \pm 10$ MeV, $M(X2) = 4664 \pm 11 \pm 5$ MeV/c^2, $\Gamma(X2) = 48 \pm 15 \pm 3$ MeV. The lighter structure is approximately at the same mass as that of BaBar, but its width is significantly smaller. Belle concludes that their states are distinct from those observed in $e^+e^- \to \pi^+\pi^- J/\psi$ by BaBar [37] and Belle [39]. A combined fit to the $\pi^+\pi^-\psi(2S)$ cross section measured by Belle and BaBar [61] yields $M(X1) = 4355^{+9}_{-10} \pm 9$ MeV/c^2, $\Gamma(X1) = 103^{+17}_{-15} \pm 11$ MeV for the $X(4360)$, and $M(X2) = 4661^{+9}_{-8} \pm 6$ MeV/c^2, $\Gamma(X2) = 42^{+17}_{-12} \pm 6$ MeV for the $X(4660)$

Ref. 52 employs the QCD string model to calculate the properties of various hybrids, and finds that the lowest vector hybrid has a mass of 4397 MeV/c^2. It also argues that strong coupling of the vector hybrid to the DD_1 and D^*D_0 modes can cause considerable threshold attraction, so that the overline vector hybrid state is responsible for formation of the near-threshold $X(4260)$ and $X(4360)$.

Ref. 62 considers the canonical charmonium assignments for the $X(4360)$ and $X(4660)$, and concludes that the latter is a good candidate for a 5^3S_1 $c\bar{c}$ state. The $X(4360)$ can be a 3^3D_1 $c\bar{c}$ state, but a charmonium hybrid interpretation cannot be excluded.

Although the width of the state observed by BaBar is larger than that of Belle, systematic uncertainties are not estimated by BaBar. We place both observations under one state $X(4360)$.

7. $X^+(4330)$ (or $Z^+(4330)$): a state in $\pi^\pm\psi(2S)$

The Belle Collaboration reports a distinct peak in the $\pi^\pm\psi(2S)$ invariant mass distribution in $B \to K\pi^\pm\psi(2S)$ decays [63]. The peak is too narrow to be caused by interference effects in the $K\pi$ channel. When fitted with a Breit-Wigner function, the mass and width of the state are $(4433 \pm 4 \pm 2)$ MeV/c^2 and (45^{+18+30}_{-13-13}) MeV, respectively.

The structure is unique in that it is the first charmonium-like candidate to have a non-zero electric charge. This could be the first observation of the tetraquark charmonium configuration. Ref. 64 notes that the mass of this structure is not far from the threshold for production of $D^*\overline{D}_1(2420)$, and suggests a production mechanism in which an anticharmed meson $\overline{c}q'$ and a charmed meson $c\overline{q}$ are produced, and rescattter to a $c\overline{c} = \psi(2S)$ and $q'\overline{q} = \pi$. To explain why the J/ψ is not produced by the same mechanism, it is assumed that rescattering may favor close values of the Q value for both sides. Ref. 65 studies whether this state could be a loosely bound molecular state of $D_1 - D^*$, or $D_1' - D^*$ arising from the one-pion-exchange potential, and concludes that such interaction alone is not sufficiently strong. At the same time, the authors of Ref. 66 claim that using QCD sum rules to describe a $D^* - D_1$ molecule with $J^P = 1^-$, they can reproduce the mass of the new state.

8. Conclusions

Note that interpretation of most of these enhancements as new resonances is not at all unambiguous; they are close to $D^{(*)}\overline{D}^{(*)}$ thresholds, where coupled-channel effects and rescattering may strongly affect the cross section. This is particularly important in such cases as the $X(3872)$, which lies right at the $D^0\overline{D}^{*0}$ threshold. Systematic searches for these states in various processes and independent confirmation are highly desirable.

References

1. S.K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **91**, 262001 (2003).
2. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. **D71**, 071103 (2005).
3. D. Acosta *et al.* [CDF II Collaboration], Phys. Rev. Lett. **93**, 072001 (2004).
4. V.M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **93**, 162002 (2004).
5. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. **D71**, 031501 (2005).
6. S. Dobbs *et al.* [CLEO Collaboration], Phys. Rev. Lett. **94**, 032004 (2005).
7. *Review of Particle Physics*, 2008.
8. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. **D77**, 011102R (2008).
9. W.M. Yao *et al.*, [Particle Data Group], J. Phys. **G33**, 1 (2006).
10. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **96**, 052002 (2006).
11. R. Chistov *et al.* [Belle Collaboration], Phys. Rev. Lett. **93**, 052803 (2004).
12. G. Gokhroo *et al.* [Belle Collaboration], Phys. Rev. Lett. **97**, 162002 (2006).
13. K. Abe *et al.* [Belle Collaboration], Belle report BELLE-CONF-0540, `arXiv:hep-ex/0505037`, paper no. LP-2005-175, contributed to the *XXII International Symposium on Lepton-Photon Interactions at High Energy*, Uppsala, Sweden, June 30 – July 5, 2005.
14. J.L. Rosner, Phys. Rev. **D70**, 094023 (2004).
15. K. Abe *et al.* [Belle Collaboration], Belle report BELLE-CONF-0541, `arXiv:hep-ex/0505038`, paper no. LP-2005-176, contributed to the *XXII International Symposium on Lepton-Photon Interactions at High Energy*, Uppsala, Sweden, June 30 – July 5, 2005.
16. A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **98**, 132002 (2007).
17. E.S. Swanson, presented at the *Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2006)*, Rio Grande, Puerto Rico, May 30 – June 3, 2006, AIP Conf. Proc. **870**, edited by T. M. Liss, p. 349.
18. H. Marsiske, in *Proceedings of the Fourth International Conference on Flavor Physics and CP Violation (FPCP*

2006), April 9 - 12, 2006 Vancouver, B.C., Canada, eConf **C060409**, 211 (2006) `[arXiv:hep-ex/0605117]`.

19. I. Kravchenko, in *Proceedings of the Fourth International Conference on Flavor Physics and CP Violation (FPCP 2006)*, April 9 - 12, 2006 Vancouver, B.C., Canada, eConf **C060409**, 222 (2006) `[arXiv:hep-ex/0605076]`.
20. W. Dunwoodie and V. Ziegler, Phys. Rev. Lett. **100**, 062006 (2008) `[arXiv:0710.5191 [hep-ex]`.
21. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. **D74**, 071101 (2006).
22. E.J. Eichten, K. Lane, and C. Quigg, Phys. Rev. **D73**, 014014 (2006) [Erratum-*ibid.* D **73**, 079903 (2006)].
23. T. Barnes, S. Godfrey, and E.S. Swanson, Phys. Rev. **D72**, 054026 (2005).
24. D. Ebert, R.N. Faustov, and V.O. Galkin, Phys. Lett. **B634**, 214 (2006).
25. F.E. Close and P.R. Page, Phys. Lett. **B578**, 119 (2004); N.A. Tornqvist, Phys. Lett. **B590**, 209 (2004); E.S. Swanson, Phys. Lett. **B588**, 189 (2004); *ibid.* **598**, 197 (2004).
26. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **93**, 041801 (2004).
27. C. Cawlfield *et al.* [CLEO Collaboration], Phys. Rev. Lett. **98**, 092002 (2007).
28. S. Uehara *et al.* [Belle Collaboration], Phys. Rev. Lett. **96**, 082003 (2006).
29. T. Barnes, S. Godfrey, and E.S. Swanson [23] obtain similar results when the 2^3P_2 mass is rescaled to 3930 MeV. See E. Swanson, AIP Conf. Proc. **814**, 203 (2006) [Int. J. Mod. Phys. A **21**, 733 (2006)].
30. T. Barnes, Oak Ridge National Laboratory Report No. ORNL-CCIP-92-05; Invited paper at *Int. Workshop on Photon-Photon Collisions*, La Jolla, CA, March 22 – 26, 1992.
31. K. Abe *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 082001 (2007).
32. T. Barnes, Int. J. Mod. Phys. **A21**, 5583 (2006).
33. P. Pakhlov *et al.* [Belle Collaboration], Phys. Rev. Lett. **100**, 202001 (2008).
34. S.-K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **94**, 182002 (2005).
35. B. Aubert *et al.* [BaBar Collaboration], `arXiv:0711.2047 [hep-ex]`.

36. H. Severini *et al.* [CLEO Collaboration], Phys. Rev. Lett. **92**, 222002 (2004).
37. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **95**, 142001 (2005).
38. Q. He *et al.* [CLEO Collaboration], Phys. Rev. **D74**, 091104 (2006).
39. C.-Z. Yuan *et al.* [Belle Collaboration], Phys. Rev. Lett. **99**, 182004 (2007).
40. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. **D73**, 011101 (2006).
41. T.E. Coan *et al.* [CLEO Collaboration], Phys. Rev. Lett. **96**, 162003 (2006).
42. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. **D73**, 012005 (2006).
43. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. **D76**, 111105 (2007).
44. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. **D76**, 012008 (2007).
45. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. **D77**, 092002 (2008).
46. C.-Z. Yuan *et al.* [Belle Collaboration], Phys. Rev. **D77**, 011105 (2008).
47. F.J. Llanes-Estrada, Phys. Rev. **D72**, 031503 (2005).
48. L. Maiani *et al.*, Phys. Rev. **D72**, 031502 (2005).
49. S.L. Zhu, Phys. Lett. **B625**, 212 (2005).
50. F.E. Close and P.R. Page, Phys. Lett. **B628**, 215 (2005).
51. E. Kou and O. Pène, Phys. Lett. **B631**, 164 (2005).
52. Yu.S. Kalashnikova and A.V. Nefediev, Phys. Rev. **D77**, 054025 (2008).
53. C. Quigg and J.L. Rosner, Phys. Lett. **B71**, 153 (1977).
54. See, for example, T. Barnes, F.E. Close, and E.S. Swanson, Phys. Rev. **D52**, 5242 (1995).
55. P. Lacock *et al.* [UKQCD Collaboration], Phys. Lett. **B401**, 308 (1997).
56. C. McNeile, C. Michael, and P. Pennanen [UKQCD Collaboration], Phys. Rev. **D65**, 094505 (2002).
57. J.L. Rosner, Phys. Rev. **D74**, 076006 (2006).
58. X. Liao and T. Manke, Columbia University Report No. CU-TP-1063, `arXiv:hep-lat/0210030`.
59. B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **98**, 212001 (2007).

60. X.-L.Wang *et al.* [Belle Collaboration], Phys. Rev. Lett. **99**, 142002 (2007).
61. Z. Q. Liu, X.S. Qin, and C.Z. Yuan, `arXiv:0805.3560 [hep-ex]`.
62. G.-J. Ding, J.-J. Zhu, and M.-L. Yan, Phys. Rev. **D77**, 014022 (2008).
63. S.-K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **100**, 142001 (2008).
64. J.L. Rosner, Phys. Rev. **D76**, 114002 (2007).
65. X. Liu *et al.*, Phys. Rev. **D77**, 034003 (2008).
66. S.-H. Lee *et al.*, Phys. Lett. **B661**, 28 (2008).