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HADRONIC B DECAYS INTO NEW CHARMONIUM LIKE STATES

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Abstract

The new charmonium-like states, $X(3872)$, $Y(3940)$, and $Z^{\pm}(4430)$, produced in B meson decays from the Belle and BaBar B-factories are reviewed. These mesons are observed in final states with the J/ψ or the $\psi(2S)$, and they do not fit into the conventional $q\overline{q}$ meson or charmonium models. They are potential candidates of 4-quark, molecule, or hybrid $gq\overline{q}$ models.

1 Introduction

The evidence for charmonium-like [1] states began with the Belle announcement in the 2003 Lepton and Photon Conference of the discovery [2] of the $X(3872)$ in the decay $X(3872) \rightarrow J/\psi\pi^+\pi^-$ in $B \rightarrow X(3872)K$. Following confirmations from the CDF, D0, and BaBar collaborations, there has been enormous interest in this state as a non-$q\overline{q}$ or exotic meson. Now more charmonium-like states from the Belle and BaBar B-factories have been discovered. All of these new charmonium-like states do not appear to fit into the conventional $q\overline{q}$ meson spectroscopy of u, d, s, c quarks and they are possible candidates for exotic states such as molecules, 4-quark states, hybrids, etc. In this ten page experimental review we discuss the latest results on the new charmonium-like states, the $X(3872)$, the $Y(3940)$ and the $Z(4430)^{\pm}$ observed in B hadronic decays from the Belle and BaBar B-factories. We begin with a brief description of the simple quark model and the charmonium model and a summary of the different production mechanisms of charmonium states in the B-factories. Then we discuss in detail the recent evidence up to September 2007, for the new charmonium-like states, the $X(3872)$, the $Y(3940)$ and the $Z(4430)^{\pm}$.

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2 $q\overline{q}$ meson model, charmonium model and Production

2.1 $q\overline{q}$ meson model

Essentially all of the experimentally observed mesons, with perhaps the exception of the light quark scalars mesons, have been fit into the simple $q\overline{q}'$ model of meson. A meson is a bound state of the spin 1/2, quark q and anti-quark $\overline{q}'$, where q and $\overline{q}'$ may be different flavors. The quark and anti-quark pair form states with total spin, $S = 0$ or 1, orbital angular momentum of $L = 0, 1, 2, ...$, and total angular momentum, J, where $|L-S| < J < |L+S|$. The parity of the state is $P = (-1)^{L+1}$ and the charge conjugation for neutral $q\overline{q}$ mesons is $C = (-1)^{L+S}$. With these simple rules, mesons are predicted using quark - antiquark combinations of $\{u, d, s, c, b\} \times \{\overline{u}, \overline{d}, \overline{s}, \overline{c}, \overline{b}\}$. Most of the predictions have been successfully observed with the correct masses, decay modes, and J^{PC}'s. A recent listing is given in the Quark Model review from the Particle Data Group [3].

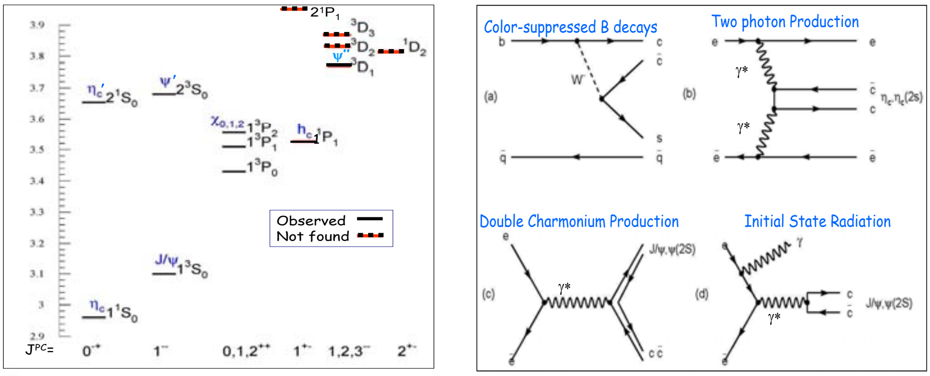

Figure 1: (Left) Charmonium Mass level diagram of observed (solid lines) and predicted states (dashed lines) and (Right) Feynman diagrams of charmonium production in B-factories.

The extensions of the $q\overline{q}$ meson model relevant to the charmonium-like states include the four-quark, molecule, and hybrid models. Some of these models were used to explain the light quark scalars and the unusual states observed in radiative J/ψ decays and recently these models have been applied to the new charmonium-like states. In the four-quark model [4] the $q\overline{q}q\overline{q}$ state forms $SU(3)$ color singlets and the simplest configurations would have S-wave 0^- and 1^- $q\overline{q}$ pairs that would lead to predictions of $J^P = 0^+, 1^+, 2^+$ four-quark states. Recent variants of the four-quark or tetraquark model include di-quarks [5]. Given that the deuteron forms a molecule, the existence of mesons forming molecules [6] might be expected. Candidate meson molecules would likely have masses near the threshold of the two meson masses and its decays could violate isospin and G-parity. A recent molecule prediction [7] of the $X(3872)$ is a $D\overline{D}^*$ molecule that decays into $J/\psi\pi^+\pi^-$ and $J/\psi\omega$. Another model was the hybrid model [8] which formed bound states of gluons and $q\overline{q}$. The hybrid models [9] have recently been applied to charmonium-like states and predict masses in the ∼4.3 GeV/c^2 region.

2.2 Charmonium Model

The Charmonium model of $c\overline{c}$ mesons is analogous to the positronium model of e^+e^- bound states. The charmonium potential models are non-relativistic, since the charm quarks have heavy masses, and models assume simple phenomenological potentials such the Cornell potential [10], $V(r) = -\kappa/r + r/a^2$, where $\kappa = 0.61$, $m_C = 1.84$ GeV/c^2, and $a = 2.38$ GeV^{-1}. These lead to fairly accurate predictions of masses, transition rates, and branching fractions. The mass predictions are drawn on the left in Fig.1 with $N^{2S+1}L_J$ labels, where we use spectroscopic notation to represent N the principle quantum number, S the total spin, L the total orbital angular momentum, and J the total angular momentum. The solid lines are the observed masses and the dashed masses are predictions of charmonium states not yet observed. The most recent charmonium state discovery is the $^1P_1$, called the h_C, observed by the CLEO group [11].

2.3 Production of charmonium-like states in B-factories

The four different production diagrams for states with charmonium, $c\overline{c}$, are shown in the diagrams on the right side in Fig.1. The Fig.1(a) is the color-suppressed B meson decay where the b quark decays via $b \to c\overline{c}s$. The Fig.1(b) is the two photon production of the $c\overline{c}$ states via the collision of two virtual photons. The Fig.1(c) is the production of a pair of $c\overline{c}$ states via a virtual photon from the e^+e^- collision that decays into $c\overline{c}$ quark pairs along with the creation of a $c\overline{c}$ sea quarks. The Fig.1(d) is the production of $c\overline{c}$ via initial state radiation (ISR) where either the electron or positron radiates a photon and creates a lower center of mass energy collision between the electron-positron pair that annihilates into a virtual photon that decays into a $c\overline{c}$ state. In this paper we review the charmonium-like states created via color-suppressed B meson decays as shown in Fig.1(a).

3 $X(3872) \to J/\psi\pi^+\pi^-$

The $X(3872)$ was the first charmonium-like state observed in color-suppressed B hadronic decays by Belle [2] in the decay, $B \to X\ K, X \to J/\psi\pi^+\pi^-$. It was subsequently confirmed in the same final state, $X \to J/\psi\pi^+\pi^-$, by the CDF, D0, and BaBar collaborations [12]. A recent remeasurement by Belle [13] of the $X(3872)$ was performed with higher statistics and the resulting $J/\psi\pi^+\pi^-$ invariant masses are shown in Figs.2(a) and (b), in the modes, $B^\pm \to X\ K^\pm, X \to J/\psi\pi^+\pi^-$ and $B^0 \to X\ K^0, X \to J/\psi\pi^+\pi^-$, respectively. The two striking properties of the $X(3872)$ were its mass, given in Table 1, which was observed right at $D^{0*}\overline{D}^0$ mass threshold, and its narrow width. The sum [14] of the D^0 and D^{*0} masses is 3871.80 ± 0.35 MeV/c^2

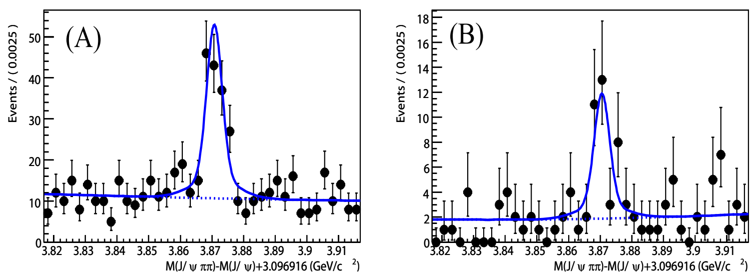

Figure 2: Recent Belle $J/\psi\pi^+\pi^-$ mass plots of X produced from charged (a) and neutral (b) B decays in $B \to XK$.

Table 1: Measured $X(3872)$ Masses (MeV/c^2)

Collaboration	$J/\psi\pi^+\pi^-$	$D\overline{D}^*$
Belle	$3872 \pm 0.6 \pm 0.5$	$3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$
Babar	3873.4 ± 1.4	$3875.1 \pm 1.1 \pm 0.5$
CDF	$3871.3 \pm 0.7 \pm 0.4$	
D0	$3871.8 \pm 3.1 \pm 3.0$	

and hence the observed X mass is $\sim$1 MeV/c^2 above this mass threshold. The mass width was less then the detector resolution and an upper limit of the width, $\Gamma(X) < 2.3$ MeV/c^2, was provided by Belle.

The search for other X charmonium decay modes led to evidence in the $X \to \gamma J/\psi$ by Belle [15] and BaBar [16]. Since the X decays into $\gamma J/\psi$ it must has C-parity +, so the $\pi^+\pi^-$ pair in the $X \to J/\psi\pi^+\pi^-$ decay, must form a C-parity - state with L=odd orbital angular momentum. The $\pi^+\pi^-$ mass has been observed by the Belle, CDF, and BaBar collaborations. The Belle [15] and CDF [17] groups finds the $\pi^+\pi^-$ mass distributions consistent with ρ^0 mass shape where the $J/\psi - \rho^0$ are in a relative S-wave. Further studies of the angular distributions indicate a preference for $J^{PC} = 1^{++}$ or 2^{-+} by CDF [17] and Belle [15] assuming only $J = 0$, 1, or 2 ruled out all assignments except $J^{PC} = 1^{++}$ and 2^{++}. Hence the combined evidence favors $J^{PC} = 1^{++}$ for the X.

Other interesting possible X decay modes include final states such as, $\omega J/\psi$, $D^{*0}\overline{D}^0$, and possibly charged partners. Belle [15] searched for $X \to J/\psi 3\pi$ and observed evidence for an X signal when the 3π mass is above 750 MeV/c^2. The rate relative to the $J/\psi\pi^+\pi^-$ is observed to be comparable, $B(X \to J/\psi 3\pi)/B(X \to J/\psi\pi^+\pi^-)$=$1.0 \pm 0.4 \pm 0.3$. Since the X is barely above the $D^{*0}\overline{D}^0$ mass threshold, a search was performed for the direct decay, $X \to D^{*0}\overline{D}^0$ and evidence [18] was found by Belle and BaBar. In Fig.3 (a) and (c) is evidence for these modes and in (b) is evidence for $B \to \psi(3770)K$, $\psi(3770) \to D\overline{D}$. The mass and product branching fractions are given in Table 1. The masses in the $D^{*0}\overline{D}^0$ final state appears to be about 3 MeV/c^2 above of the nominal X mass that is observed in the $J/\psi\pi^+\pi^-$ final state. This apparent mass shift could be explained [19] as a shift of the $D^{*0}\overline{D}^0$ final state mass which is sensitive to its orbital angular momentum due to the closeness of the $D^{*0}\overline{D}^0$ mass threshold.

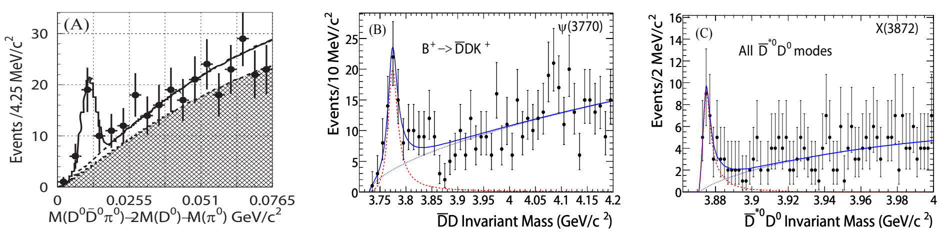

Figure 3: (a) The Belle $M(D^0\overline{D}^0\pi^0) - M(D^0\overline{D}^0)$ mass difference in $B \to D^0\overline{D}^0\pi^0 K$. (b) The BaBar $M(D^0\overline{D}^0)$ mass in $B \to D^0\overline{D}^0 K$ and (c) the $M(D^0\overline{D}^0\pi^0)$ mass in $B \to D^0\overline{D}^0\pi^0 K$.

4 $Y(3940) \to J/\psi\omega$

The $Y(3940)$ was the second charmonium-like particle to be observed in B decays. This was first observed by the Belle collaboration [20], produced in $B \to YK^+$ and YK_S with $Y \to J/\psi\omega$. This has been recently confirmed by the BaBar collaboration. The Belle analysis, using 275×10^6 $B\overline{B}$ pairs, selected $B \to J/\psi\pi^+\pi^-\pi^0K^+/K_S$ event candidates. Evidence for the three body final decay, $B \to J/\psi\omega K^+/K_S$, was apparent when signal peaks in the M_{BC}, ΔE, and 3π mass distributions were observed. After restricting $0.760 < M(3\pi) < 0.805$ GeV to select ω candidates and requiring the event candidates to have the correct M_{BC} and ΔE values, a Dalitz plot was created which is shown in Fig.4(a). The Dalitz plot has $K\omega$ events $M^2(K\omega)$ $\sim$2 $(\mathrm{GeV/c^2})^2$ and Belle interprets this from strange mesons, such as the $K_1(1270)$, $K_1(1400)$, or $K_2^*(1430)$, decaying into $K\omega$. To remove these possible backgrounds a $M(K\omega) < 1.6$ GeV cut is applied as shown in Fig.4(a) by the vertical line. The event candidates are selected in twelve 40 MeV wide bins of $M(J/\psi\omega)$ starting at 3.880 GeV and their M_{BC} mass distributions are fit with a gaussian signal function and an ARGUS background function. The number of signal events and its error for each $M(J/\psi\omega)$ bin is plotted in Fig.4 (b). The binnned $M(J/\psi\omega)$ distributions represent pure signal events, when the ω mass is restricted to $0.760 < M(3\pi) < 0.805$ GeV. A large enhancement in the first three 40 MeV bins is visible at threshold. A pure phase space curve starting near zero at 3.880 MeV is drawn in Fig.4(B). The mass distribution is fit with a Breit-Wigner curve producing a signal yield of 58 ± 11 events, a mass of $M = 3942 \pm 11$ MeV, and a width of $\Gamma = 87 \pm 22$ MeV. The resulting signal fit is shown in Fig.4 (c). The BaBar collabora-

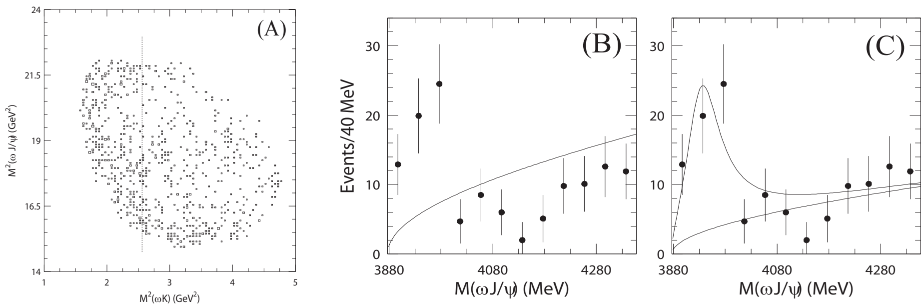

Figure 4: (a) Belle Dalitz plot of the three body decay $B \to J/\psi\omega K$ with $M^2(\omega J/\psi)$ versus $M^2(K\omega)$. (b)The mass plot $M(J/\psi\omega)$ with a pure phase space curve and (c) a signal Breit-Wigner curve plus a pure phase space curve.

tion [21] has recently confirmed the evidence for the $Y \to J/\psi\omega$ with higher statistics based on a 350 fb^{-1} data sample. The $B \to J/\psi\pi^+\pi^-\pi^0K^+/K_S$ events are selected with $0.7695/0.7605 < M(3\pi) < 0.7965/0.8055$ GeV for the B^+/B^0 modes. The M_{ES} distributions contained in each $M(J/\psi\omega)$ bin are fit to extract the number of $B \to J/\psi\pi^+\pi^-\pi^0K^+/K_S$ signals. Since a narrow structure appears near threshold, the $M(J/\psi\omega)$ bins are chosen to be ten narrow 10 MeV bins from 3882.5 to 3982.5 MeV and sixteen wider 50 MeV bins starting at 3982.5 MeV. Evidence for a signal near threshold appears in the charged and neutral B meson modes. The acceptance corrected plot for the charged and neutral B decay modes are shown in Fig.5. The

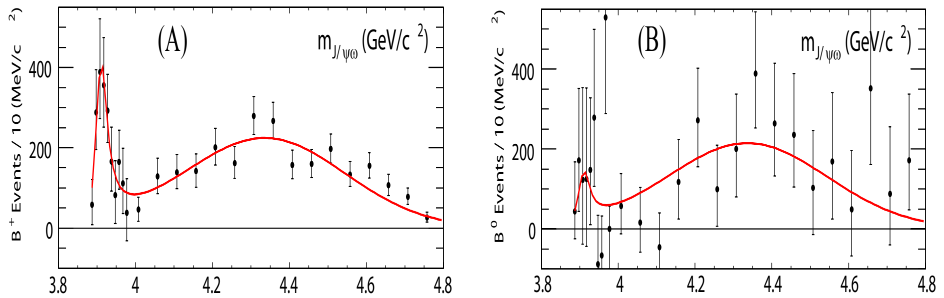

Figure 5: The BaBar $M(J/\psi\omega)$ mass distributions from (a) $B^+ \to J/\psi\omega K^+$ and (b) $B^0 \to J/\psi\omega K_S$.

two mass distributions are fit simultaneously with a Breit-Wigner curse producing a signal, $Y \to J/\psi\omega$, with a mass of $M = 3914.6^{+3.8}_{-3.4}(stat.)^{+1.9}_{-1.9}(syst.)$ MeV/c^2, and a width of $\Gamma = 33^{+12}_{-8}(stat.)^{+5}_{-5}(syst.)$ MeV/c^2. The higher statistics BaBar Y results compared with the Belle results, have narrower and lower mass values.

5 $Z^{\pm}(4430) \to \psi(2S)\pi^{\pm}$

The $Z^{\pm}(4430)$ particle is the latest discovery announced by Belle [22] at the 2007 Lepton-Photon Conference. The remarkable aspect of this candidate state is a final state, $\psi(2S)\pi^{\pm}$, which is a charged charmonium-like state. The conventional quark model does not permit mesons to strongly decay into a charged state with hidden charm (or strangeness). Of course weak decays into final states such as $D_S^+ \to \phi\pi^+$ or $B^+ \to J/\psi K^+$ are predicted and observed, but no strong or OZI-allowed decays can create charged hidden charm and none until now have been observed. Hence this candidate is a *smoking gun* or irrefutable evidence for an exotic meson.

This particle is produced in color-suppressed B decays, $B \to \psi(2S)\ \pi^{\pm}$ $K^{\mp}/K_S$. The events are based on an Belle integrated data sample of 605 fb^{-1}. The Dalitz plot of this three body decay is shown Fig.6(a). There is visual evidence for at least three quasi-twobody decays, $B \to \psi(2S)K^*(890)$ with $K^* \to K\pi$, $B \to \psi(2S)K_2^*(1430)$ with $K_2^* \to K\pi$, and a new state, $B \to Z^{\pm}(4430)K$ with $Z^{\pm} \to \psi(2S)\pi^{\pm}$. The obvious vertical bar at $M(K\pi)^2$ $\approx$ 0.8 (GeV/c^2)^2 is the decay, $K^*(890) \to K\pi$ and a weaker wide vertical line at $M(K\pi)^2 \approx 2$ (GeV/c^2)^2 may be the $K_2^*(1430) \to K\pi$. A horizontal line is evident near $M(\psi(2S)\pi^{\pm})^2 \approx 19.6$ (GeV/c^2)^2 indicating a $\psi(2S)\pi^{\pm}$ resonance with mass $\sim$ 4.4 GeV/c^2. The $\psi(2S)\pi^{\pm}$ mass plot is shown in Fig.6(b) and a peak is evident at $\sim$ 4.43 Gev/c^2 over a broad background which is presumably due to the $B \to \psi(2S)K^*(890)$ signal. This 4.43 Gev/c^2 state was named by Belle, the $Z(4430)$. In a related mode, BaBar has studied, $B \to J/\psi K^*$, and observed that the K^* resonances include the $K^*(890)$, $K_2^*(1430)$, and a broad S-wave $K\pi$ in the 1.1-1.3 GeV/c^2 mass region. We would expect the similar K^* resonances produced in $B \to \psi(2S)K^*$. It is possible that in the Dalitz plot the $Z^{\pm}$ interferes with the S-wave $K\pi$ as the intensity of the events along 19.6 $(GeV/c^2)^2$ horizontal line varies. Belle fit

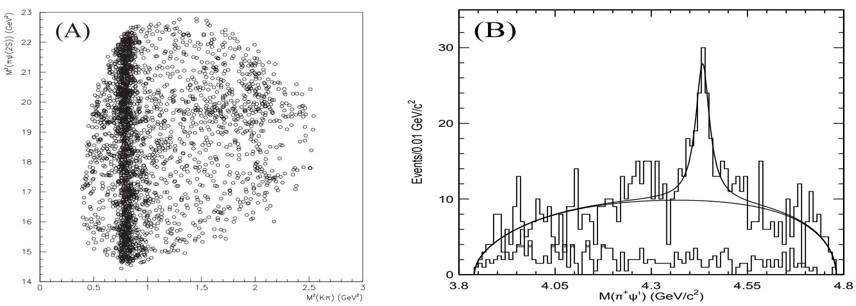

Figure 6: (a) The Belle Dalitz plot of $M^2(\psi(2S)\pi^{\pm})$ versus $M^2(K\pi^{\pm})$. (b) The Belle $M(\psi(2S)\pi^{\pm})$ mass plot.

the $M(\psi(2S)\pi^{\pm})$ mass plot and obtained a mass of $4433 \pm 4(stat) \pm 1(syst)$ GeV/c^2, a width of $44^{+17}_{-13}(stat)^{+30}_{-11}(syst)$ GeV/c^2, and a branching fraction of $BF(B \to KZ^{\pm},\ Z^{\pm} \to \psi(2S)\pi^{\pm}) = 4.1 \pm 1.0(stat) \pm 1.3(syst) \times 10^{-5}$.

Since the evidence for the $Z^{\pm}$ is very recent, we discuss some implications of this new candidate state. In the color-suppressed B decay into three bodies, $\psi(2S)\pi^{\pm}K^{\mp}$, we would expect and observe the conventional quasi-twobody decay to be the $B \to \psi(2S)K^*$, $K^* \to \pi^{\pm}K^{\mp}$ as shown in Fig.7 (a). The alternate combination in Fig.7 (b), would indicate the $Z^{\pm}$ is formed with $c\bar{c}u\bar{d}$ quarks or perhaps two mesons containing this combination of four

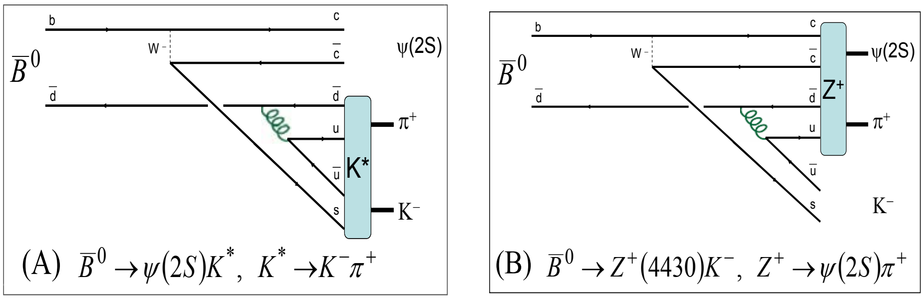

Figure 7: The Feynman diagram for color-suppressed B decay,(a) $\overline{B}^0 \to \psi(2S)\overline{K}^{*0}, \overline{K}^{*0} \to K^-\pi^+$ and (b) $\overline{B}^0 \to Z^+K^-$, $Z^+ \to \psi(2S)\pi^+$.

quarks. The $Z^\pm$ may be a bound state [23] of $c\bar{c}u\overline{d}$ quarks. Since the mass of the $Z^\pm$ is near the sum of the masses of the $D^*(2010)$ and $D_1(2420)$, the $Z^\pm$ may be a molecule [24] formed with these two mesons. If the $\psi(2S)$ and $\pi^\pm$ are in a relative L=0 wave, then the $Z^\pm$ has $J^P = 1^+$, and we might expect other $Z^\pm$ decays to include $\eta_C\rho$ and $D\overline{D}^*$. If the $\psi(2S)$ and $\pi^\pm$ are in a relative L=1 wave, then the $Z^\pm$ could be $J^P = 0^-$, 1^-, or 2^-, and we might expect other $Z^\pm$ decays to include $J/\psi a_0(980)$, $\eta_C b_1(1235)$, $h_C\pi$, and $D\overline{D}_1(2420)$. Assuming isospin is not severely violated we would expect to find the neutral decay, $Z^0(4430) \to \psi(2S)\pi^0$. A mysterious question is why the simpler and experimentally easier to detect decays such as $Z^\pm \to J/\psi\pi^\pm$ or $Z^\pm \to J/\psi\rho^\pm$ [25] have not been found. If it indeed turns out to be the case that $Z^\pm \to J/\psi\pi^\pm$ is suppressed whereas $Z^\pm \to \psi(2S)\pi^\pm$ is allowed, this perhaps may be related to the longstanding $\rho\pi$ puzzle [26] in hadronic J/ψ and $\psi(2S)$ decays where experimentally we observe $J/\psi \to \rho\pi$, but for unknown reasons $\psi(2S) \to \rho\pi$ is highly suppressed.

6 Summary

In summary we discussed the new charmonium-like particles, the $X(3872)$, the $Y(3940)$, and the $Z(4430)$. These new discoveries observed in experiments at the B-factories and Tevatron collider, are candidates for non-$q\overline{q}$ or exotic mesons. The narrow $X(3872)$ due to its mass proximity to $D\overline{D}^*$ is likely to be a molecular meson. The $Y(3940)$ may be a candidate for a hybrid charmonium. The $Z(4430)$, if confirmed, is perhaps the most compelling exotic meson found to date, being a state with charged hidden charm that must be a four-quark state or possibly a molecule. With more data expected, confirmations and new results are possible in the next two years.

Acknowledgments

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[1] By charmonium-like, we mean a resonance whose a final state contains a charmonium, $c\bar{c}$, meson such as the J/ψ, $\psi(2S)$, η_C, χ_C, etc., but is not a predicted by the conventional charmonium model.

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