

Recent Results in Charmonium Spectroscopy at *B*-factories

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Charmonium spectroscopy gained renewed interest after the discovery in 2003 of the unpredicted $X(3872)$ charmonium-like state, above the $D\bar{D}$ threshold. To date many charmonium-like states above the $D\bar{D}$ threshold have been claimed. Some of these states do not easily fit the conventional charmonium picture. In this article we review recent experimental results in this field, reported by the *BABAR* and Belle Collaborations.

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1. Introduction

Since the discovery of the J/ψ in 1974 [1], the study of charmonium spectroscopy has provided crucial tests of the quark model and of models of the QCD interaction. The charmonium spectrum cannot be derived directly from the QCD Lagrangian, due to the presence of large non-perturbative effects at this energy. The charmonium spectrum may be predicted by constituent quark model inspired potential models [2] that include a Coulomb-like one-gluon-exchange term at short distance and a linear confining contribution in the long range. In this picture each state is characterized by J^{PC} quantum numbers, where $J = L + S$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$, L is the orbital angular momentum, and S the total spin. Allowed J^{PC} quantum numbers in constituent quark model are 0^{++} , $1^{\pm-}$, 1^{++} , 2^{++} , Charmonium resonances are expected to be narrow below the $D\bar{D}$ threshold, and wide above, due to the accessibility of Zweig favored decays.

In 2003, the Belle Collaboration reported the observation of a narrow charmonium-like state decaying into $J/\psi \pi^+ \pi^-$, with a mass of about 3872 MeV/ c^2 [3]. This state, dubbed $X(3872)$, was then confirmed by the CDF [4], D0 [5], and *BABAR* [6] Collaborations. This state is above the open-flavor threshold, but has a width of only $3.0_{-1.7}^{+2.1}$ MeV/ c^2 [7], and cannot easily fit into the charmonium picture provided by the potential model. The search for the same final state in initial state radiation (ISR) production resulted in the observation by *BABAR* of the $Y(4260)$ with a mass of about 4260 MeV/ c^2 and a width of about 90 MeV/ c^2 [8]. This state has been confirmed by the CLEO [9] and Belle [10] Collaborations. Other states decaying into $J/\psi \pi^+ \pi^-$ and $\psi(2S) \pi^+ \pi^-$ have been claimed or observed in ISR production [10, 11].

Several new states have been observed by both *BABAR* and Belle in the 3940 MeV/ c^2 region, including $X(3915)$ [12], $X(3940)$, $X(4160)$ [13], $Y(3940)$ [14, 15], and $Z(3930)$ [16, 17]. A narrow resonance-like state decaying into $J/\psi \phi$ and dubbed $Y(4140)$ was claimed by CDF [18], but not confirmed by Belle [19, 20]. However, Belle reports evidence of another resonance, the $X(4350)$, in the same final state [20]. In 2007, the Belle Collaboration claimed the observation of a narrow state carrying hidden charm and decaying to an electrically charged final state [21]. This state, dubbed $Z(4430)$, was searched and not confirmed by *BABAR* [22]. Two more charged charmonium-like states were reported by Belle [23].

The theoretical interpretation of these new states is not trivial and often not widely accepted by the whole scientific community. There are some exotic states that are predicted by QCD, but were never clearly established. The presence of the gluon field in the QCD Lagrangian allows for the existence of mesons with an excited gluonic degree of freedom (hybrids) [24]. The possible existence of multi-quark states, including tetraquarks [25, 26], pentaquarks [27], hexaquarks [28], and loosely bound $D\bar{D}$ molecules [29, 30, 31] have been investigated. Recently the possible existence of *hadrocharmonium* states, i.e. conventional $c\bar{c}$ states coated by light hadrons, has been studied [32]. Finally, these states may originate from threshold rescattering or channel coupling [33]. The unusual properties of the new charmonium-like states, such as small width and large branching ratios into final states without open charm, may be explained inside these exotic frameworks. It should be noted that only multi-quark states and *hadrocharmonium* are compatible with non-zero electric charge.

In this article, I will review recent experimental results about new charmonium-like states. Conventional charmonium spectroscopy is not covered. Furthermore, due to space limit, I will

not cover results related to $X(3940)$, $X(4160)$, and the $J^{PC} = 1^{--}$ states observed in the 4260–4660 MeV/ c^2 region. A comprehensive review of charmonium spectroscopy may be found in [25, 34].

2. Experimental techniques

Results presented in this paper are obtained using data collected by *BABAR*, Belle and CDF detectors, whose detailed description may be found in [35, 36, 37], respectively. At CDF a proton and an anti-proton are collided at a center of mass energy $\sqrt{s} = 1.96$ TeV. The $c\bar{c}$ states are produced both promptly or in B meson decays. At B -factories, several production processes may be exploited:

- B meson decay: exotic $c\bar{c}$ states are studied in $B \rightarrow (c\bar{c})K^{(*)}$ with the subsequent decay of $c\bar{c}$ into the desired final state. The B meson is discriminated against $q\bar{q}$ background using kinematic variables such as $\Delta E \equiv E_B - \frac{1}{2}\sqrt{s}$ and $m_{ES} \equiv \sqrt{s/4 - \vec{p}_B^2}$, where (E_B, \vec{p}_B) is the B meson four-momentum vector expressed in $Y(4S)$ rest frame and \sqrt{s} is the center-of-mass energy;
- ISR production: $c\bar{c}$ is produced in $e^+e^- \rightarrow c\bar{c}\gamma_{ISR}$, where γ_{ISR} is a photon radiated by the incoming electron or positron. Since $c\bar{c}$ couples directly to the virtual photon, $J^{PC} = 1^{--}$.
- Two-photon collision: $c\bar{c}$ is produced in the $e^+e^- \rightarrow \gamma\gamma e^+e^- \rightarrow c\bar{c}e^+e^-$ process. Usually the outgoing electrons are not detected, so the photons are quasi-real. This implies that the accessible J^{PC} numbers are $0^{\pm+}$ and $2^{\pm+}$ [38]. Spin-parity numbers with $J > 2$, that are allowed in two-photon production, are expected to be suppressed, due to the limited phase space available to the decay.
- Double charmonium production: the $c\bar{c}$ state is produced recoiling against a J/ψ in the $e^+e^- \rightarrow J/\psi(c\bar{c})$ process. C -parity is positive. So far only $J = 0$ states have been observed.

The $c\bar{c}$ decay is usually fully reconstructed. Inclusive searches have been performed in double charmonium production [13]. Information on J^{PC} numbers may be inferred from the properties of the production mechanism and the studied final state, and by studying the angular distribution of $c\bar{c}$ decay products.

3. $X(3872)$

Quite a large number of experimental results is available for the $X(3872)$. At B -factories, $X(3872)$ has been searched in B meson decays. The $J/\psi\pi^+\pi^-$ decay mode, where this state was discovered [3], also provides insight on its nature. The $\pi^-\pi^-$ mass distribution is consistent with subthreshold ρ production [39]. The CDF Collaboration has performed a full angular analysis of the decay products, excluding all the possible J^P numbers, but 1^+ and 2^- [40]. Belle has performed a spin-parity analysis using 256 fb^{-1} [41] of data. The number of reconstructed $X(3872)$ is insufficient to perform a full angular analysis. Instead, a study of angular distributions suggested in [42] favors a 1^{++} assignment. It should be noted that the angular analysis performed is insensitive to $J > 1$. However, the study of $\pi^+\pi^-$ mass distribution gives some insight on the state parity. In

fact, the mass distribution near the kinematic endpoint is suppressed by a centrifugal barrier factor. Belle analysis agrees with $P = +1$ at 28% level (agreement with $P = -1$ is at 0.1% level). This excludes $J^{PC} = 2^{-+}$.

Decay to $D^0\bar{D}^0\pi^0$ has been observed [43] and interpreted as $D^0\bar{D}^{*0}$. This interpretation has been confirmed in subsequent analyses [44].

Belle reported evidence of the decay into $J/\psi\pi^+\pi^-\pi^0$ [45]. The three pion mass distribution is consistent with subthreshold ω production. The ratio of branching fractions $\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^-\pi^-)$ is $1.0 \pm 0.4(stat) \pm 0.3(syst)$. Recently, *BABAR* has reported evidence of decay into the $J/\psi\omega$ final state with a significance of 4 standard deviations (σ) [46]. The angular distribution of the three-pion system strongly supports their origin from an ω . The ratio $\mathcal{B}(X(3872) \rightarrow J/\psi\omega)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^-\pi^-)$ is equal to 0.7 ± 0.3 and 1.7 ± 1.3 , for charged and neutral B decays, respectively, where the error is the sum in quadrature of the statistical and systematic uncertainties. An analysis of the three pions mass distribution, similar to the one in [41], is performed. The agreement with $P = -1$ (61.9%) is far better than with $P = +1$ (7.1%). Thus, $J^{PC} = 2^{-+}$ is favored, in contrast with Belle [41].

Radiative $X(3872)$ decay into $J/\psi\gamma$ has been observed by *BABAR* [47] and Belle [45]. This observation implies that the $X(3872)$ has positive C-parity. *BABAR* reports an evidence of the decay into $\psi(2S)\gamma$ final state [47] at 3.5σ level, using a data sample of 424 fb^{-1} . The measured branching fraction ratio $\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)/\mathcal{B}(X(3872) \rightarrow J/\psi\gamma) = 3.4 \pm 1.4$, where the error is the sum in quadrature of the statistical and systematic uncertainties, is unexpectedly large. Recently, Belle reported a preliminary result [48] of a search for $\psi(2S)\gamma$ decay using 849 fb^{-1} of data. No statistically significant signal is observed. The branching fraction upper limit at 90% confidence level is $\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)/\mathcal{B}(X(3872) \rightarrow J/\psi\gamma) < 2.1$.

A common agreement concerning the interpretation of $X(3872)$ has not been reached. Possible conventional charmonium assignments are χ'_{c1} or $\eta_{c2}(1D)$. The first is challenged by the fact that χ'_{c2} is tentatively identified as the $Z(3930)$. This implies that the mass splitting in the χ'_c triplet should be larger than expected. However, it was noticed that the effect of the coupling to $D\bar{D}^*$ channel may shift the 1^{++} state mass down to $D\bar{D}^*$ threshold, while the shift of the 2^{++} state is expected to be much smaller [49]. The $\eta_{c2}(1D)$ interpretation is favored by *BABAR* assignment of $J^{PC} = 2^{-+}$. The measured $X(3872)$ mass is consistent with the 1^1D_2 state mass predicted in [50], but not consistent with the values reported in many recent papers [51]. Theoretical calculations [52, 53] shows that the predicted decay rate of such a state to $\psi(2S)\gamma$ is inconsistent with the results reported by *BABAR* [47]. It should be noted that recent Belle preliminary result for this decay mode disagrees with *BABAR* one [48]. Recently it has been noticed that also the decay rate to $D^0\bar{D}^{*0}$ cannot fit the 1^1D_2 assignment [53]. $X(3872)$ interpretation as a $D^0\bar{D}^{*0}$ molecule was suggested by many authors [30, 31, 54], and may accommodate the observed large isospin violation [31]. However, the decays into $J/\psi\gamma$ and $\psi(2S)\gamma$ imply that this molecular state should mix with χ'_{c1} [55]. Such a mixing may be not as large as proposed, in the light of the new Belle result on $\psi(2S)\gamma$ decay [48]. Molecular interpretation is challenged by *BABAR* $J^{PC} = 2^{-+}$ assignment. Furthermore, it was noticed that the molecular interpretation may be inconsistent with the large cross section for prompt production that can be derived from CDF results [56]. The interpretation of $X(3872)$ as a tetraquark [57] predicts the presence of neutral and charged partners in the same mass region. Such states were searched and not found [58].

4. The 3940 Family

The $Y(3940)$ was observed by Belle in the $B \rightarrow J/\psi \omega K$ process [14], and confirmed by *BABAR* [15]. The same structure is not observed in the $B \rightarrow D^0 \bar{D}^{*0} K$ process [44]. Belle measures the mass $(3943 \pm 11(stat) \pm 13(syst))$ MeV/ c^2 and width $(87 \pm 22(stat) \pm 26(syst))$ MeV/ c^2 . A resonance in the the $J/\psi \omega$ final state, dubbed $X(3915)$, was observed by Belle in two-photon collisions [12]. The measured mass and width are $(3914 \pm 3(stat) \pm 2(syst))$ MeV/ c^2 and $(17 \pm 10(stat) \pm 3(syst))$ MeV/ c^2 , respectively. A recent *BABAR* re-analysis [46] provides a $Y(3940)$ mass and width of $(3919.1^{+3.8}_{-3.5}(stat) \pm 2.0(syst))$ MeV/ c^2 and $(31^{+10}_{-8}(stat) \pm 5(syst))$ MeV/ c^2 , respectively. This latter measurement favors a $Y(3940)$ mass slightly lower than the one first reported by Belle [14]. This value is in agreement with the one measured by Belle for the $X(3915)$ in the two-photon process. Thus, it seems likely that the same particle, with a mass of about 3915 MeV/ c^2 , is observed in two distinct production processes. Belle reports a product of the two-photon width times the decay branching ratio $\Gamma_{\gamma\gamma}(Y(3940)) \times \mathcal{B}(Y(3940) \rightarrow J/\psi \omega)$ equal to $(61 \pm 17(stat) \pm 8(syst))$ eV and $(18 \pm 5(stat) \pm 2(syst))$ eV for $J^P = 0^+$ and 2^+ assignments, respectively [12]. Assuming $\Gamma_{\gamma\gamma}(Y(3940)) \sim 1$ keV, that is a typical value for excited charmonium, the branching ratio $\mathcal{B}(Y(3940) \rightarrow J/\psi \omega)$ is in the range 1–6%, which is unexpectedly large, compared to other excited $c\bar{c}$ states [59]. The proposed interpretation of $Y(3940)$ as the χ'_{c1} state, where the final state interaction enhances the $J/\psi \omega$ decay [34], is ruled out by the observation of this state in two-photon production. Interpretation as χ'_{c0} was also suggested [60]. Interpretation as a charmonium hybrid is seriously challenged by lattice calculations that show that the expected mass for hybrid ground state should be some 500 MeV/ c^2 higher than the one of $Y(3940)$. Interpretation in the framework of molecular model has been proposed [61, 62, 63]. It was suggested that the decay into $D^* \bar{D} \gamma$ may give more insight on the nature of this state [63].

Another resonant state, dubbed $Z(3930)$, was observed by Belle [16] and confirmed by *BABAR* [17]. It was studied in two-photon production process and $D\bar{D}$ final state. The measured mass and width are $(3929 \pm 5(stat) \pm 2(syst))$ MeV/ c^2 and $(29 \pm 10(stat) \pm 2(syst))$ MeV/ c^2 for Belle and $(3927 \pm 2(stat) \pm 1(syst))$ MeV/ c^2 and $(21 \pm 7(stat) \pm 4(syst))$ MeV/ c^2 for *BABAR*. The agreement between the two measurements is very good. The decay into spinless final state, combined with the fact that $C = +1$ due to the production mechanism, implies that $J = L$ is even and thus $P = +1$. The value of J is determined by studying the angular distribution of the decay products. In particular, the angle between the directions of the $D\bar{D}$ system and the beam provides such kind of information. Both experiments favor $J^{PC} = 2^{++}$ assignment. Belle provides a measurement of the branching fraction ratio $\mathcal{B}(Z(3930) \rightarrow D^+ D^-) / \mathcal{B}(Z(3930) \rightarrow D^0 \bar{D}^0) = 0.74 \pm 0.43(stat) \pm 0.16(syst)$ which suggests isospin invariance, as expected for conventional $c\bar{c}$. The product of the two-photon width times the decay branching ratio $\Gamma_{\gamma\gamma}(Z(3930)) \times \mathcal{B}(Z(3930) \rightarrow D\bar{D})$ is found to be (0.18 ± 0.06) keV and (0.24 ± 0.05) keV, by Belle and *BABAR*, respectively, where the error is the sum in quadrature of the statistical and systematic uncertainties. There is a general agreement about the interpretation of this state, which is identified as χ'_{c2} . The mass, two-photon width and decay angular distribution are consistent with theoretical expectation for this charmonium state [50, 64].

5. New $J/\psi \phi$ States

The search of structures in the $J/\psi \phi$ mass spectrum is motivated by the prediction that a $c\bar{c}s\bar{s}$ tetraquark is expected to have sizable branching ratio in this final state and a mass in the 4270–4350 MeV/ c^2 range [73]. CDF has reported an evidence of a resonance-like candidate, dubbed $Y(4140)$, with a significance of 3.8σ [18]. The $J/\psi \phi$ final state was studied in $B^+ \rightarrow J/\psi \phi K^+$ decay. The measured mass and width are $(4143.0 \pm 2.9(stat) \pm 1.2(syst))$ MeV/ c^2 and $(11.7^{+8.3}_{-5.0}(stat) \pm 3.7(syst))$ MeV/ c^2 . A subsequent document by CDF estimates the branching fraction product $\mathcal{B}(B^+ \rightarrow Y(4140)K^+) \times \mathcal{B}(Y(4140) \rightarrow J/\psi \phi) = (9.0 \pm 3.4(stat) \pm 2.9(syst)) \times 10^{-6}$ [74]. Belle has searched for the $Y(4140)$ using the same production mechanism, and found no evidence of it [19]. However, due to small detection efficiency near the $J/\psi \phi$ threshold, the upper limit on the branching ratio $\mathcal{B}(B^+ \rightarrow Y(4140)K^+) \times \mathcal{B}(Y(4140) \rightarrow J/\psi \phi) < 6 \times 10^{-6}$ is not in contradiction with CDF measurement, considering its large uncertainty. Several interpretation were proposed for $Y(4140)$, including a $D_s^{*+}D_s^{*-}$ molecule [62, 65, 66, 67], an exotic 1^{-+} hybrid [67], a $c\bar{c}s\bar{s}$ tetraquark [68], and an effect of the $J/\psi \phi$ threshold opening [69]. Some arguments were raised against the interpretation as a standard $c\bar{c}$ state [70] and scalar $D_s^{*+}D_s^{*-}$ molecule [71]. Authors of Ref. [62] predict, in the $D_s^{*+}D_s^{*-}$ molecule picture, the product of the two-photon width times the decay branching ratio $\Gamma_{\gamma\gamma}(Y(4140)) \times \mathcal{B}(Y(4140) \rightarrow J/\psi \phi)$ to be sizable, with large theoretical uncertainties. Belle searched for the $Y(4140)$ in two-photon production and found no evidence of it [20]. Furthermore, Belle has reported evidence of a narrow structure with a mass equal to $(4350^{+4.6}_{-5.1}(stat) \pm 0.7(syst))$ MeV/ c^2 and width $(13^{+18}_{-9}(stat) \pm 4(syst))$ MeV/ c^2 . The structure, dubbed $X(4350)$, has a significance of 3.2σ . The measured mass is inconsistent with the $Y(4140)$ one. Interpretation of the $X(4350)$ as χ''_{c2} was suggested [60]. Other interpretations as an exotic state are similar to the $Y(4140)$ ones [66, 68, 72].

6. Charged States

The observation of a resonance-like state with non-zero net electric charge would be striking evidence of a state with an unconventional nature, since it would be inconsistent with the $q\bar{q}$ structure. In particular, both multiquark states and *hadrocharmonium* may accommodate such non-zero charge. Belle reported the evidence of the narrow $Z(4430)^-$ decaying into $\psi(2S)\pi^+$, with a significance of 5.4σ [75]. This state was studied in the decay $B^0 \rightarrow \psi(2S)\pi^-K^+$. The Dalitz plot of this decay is dominated by the presence of the K^* resonances. In Belle's first analysis, a veto was applied to remove such contributions [21]. In a more recent analysis, a full Dalitz plot analysis was performed [75]. Both analyses report the same value for the mass $(4433^{+15}_{-12}(stat)^{+19}_{-13}(syst))$ MeV/ c^2 [75]. The measured widths are equal to $(45^{+18}_{-13}(stat)^{+30}_{-13}(syst))$ MeV/ c^2 and $(107^{+86}_{-43}(stat)^{+74}_{-56}(syst))$ MeV/ c^2 , in the first [21] and latter [75] analysis, respectively. These measurements are consistent inside the large uncertainties of the latter. *BABAR* has searched for the $Z(4430)$ in both $J/\psi \pi^-$ and $\psi(2S)\pi^-$ final states, but no evidence of resonance-like structures has been found [22]. In this analysis, *BABAR* has performed a study of the reflections of the K^* system in the $J/\psi(\psi(2S))\pi^-$ mass spectrum, and found that such reflections reproduce data well, without the need of any additional resonant structures. The upper limit at 90% confidence level on the branching fraction product $\mathcal{B}(B^0 \rightarrow Z(4430)^-K^+) \times$

$\mathcal{B}(Z(4430)^- \rightarrow \psi(2S)\pi^-)$ reported by *BABAR* is 3.1×10^{-5} . This is not in contrast with the measured value $(3.2_{-0.9}^{+1.8+5.3}) \times 10^{-5}$ reported by Belle. No analysis of the $J/\psi \pi^-$ final state has been reported by Belle so far.

Belle reported evidence of two more states ($Z_1(4050)^-$ and $Z_2(4250)^-$) with non-zero electric charge in the final state $\chi_{c1}\pi^-$ [23]. These states were found in $B \rightarrow \chi_{c1}\pi^- K$, whose Dalitz plot is dominated by the K^* resonances. A Dalitz plot analysis is performed. The solution with two resonant structures is favored with respect to the one with no resonant contributions, with a significance of 5.7σ . The mass of these states is $(4051 \pm 14(stat)_{-41}^{+20}(syst))$ MeV/ c^2 and $(4248_{-28}^{+44}(stat)_{-35}^{+180}(syst))$ MeV/ c^2 , respectively. Their width is $(82_{-17}^{+21}(stat)_{-22}^{+47}(syst))$ MeV/ c^2 and $(177_{-39}^{+54}(stat)_{-61}^{+316}(syst))$ MeV/ c^2 , respectively. No search for such states has been reported by *BABAR* so far.

7. Conclusions

In conclusion, recent advances on both theoretical and experimental sides concerning charmonium spectroscopy have brought renewed interest in this field. Unusual properties of newly discovered states may suggest that they represent some form of hadronic matter predicted by QCD but never observed so far, such as multiquarks or molecular states. Some of the new states are well established experimentally, such as $X(3872)$ and $Y(4260)$, but the determination of their properties and the theoretical interpretation is still an open issue. In particular, the recent $X(3872)$ measurement in the $J/\psi \omega$ final state by *BABAR* [46] favors a $J^{PC} = 2^{-+}$ assignment, opposed to 1^{++} as generally accepted previously. New measurements of the properties of such a state, also at hadronic machines, may shed light on its nature. Many other states have been claimed, but are missing confirmation. Among them, the most interesting are the Z^- states that exhibit non-zero electric charge. A confirmation of such states would be a compelling evidence of the existence of mesons with non- $q\bar{q}$ structure. The observation of $Z(4430)$ was claimed by Belle [21] and not confirmed by *BABAR* [22]. This state is in principle accessible at the Tevatron and LHC experiments. Alternatively, the search for $Z_1(4050)^-$ and $Z_2(4250)^-$ at hadronic machines could be quite tricky, or even unfeasible, since the χ_{c1} is reconstructed through its $\chi_{c1} \rightarrow J/\psi \gamma$ decay, where the photon has an energy of about 410 MeV. An ideal environment to perform measurements of exotic charmonia properties and searches for new states would be the future super-flavor factories SuperB [76] and SuperKEKB [77].

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