RECENT PROGRESS AND PUZZLES IN CHARMONIUM PHYSICS*

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While the charmonium model has been effective in describing $c\bar{c}$ bound mesons, there have been many recently discovered charmonium-like states it cannot accommodate. Here I provide a review of recent results from the B-factories including the $X(3872)$, three new particles in the mass range near 3.93 GeV/c^2, and four new resonances in initial state radiation (ISR) decays.

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1. Introduction

The charmonium model is a phenomenological model describing the bound state of the charm and anti-charm quark system [1]. Figure 1 demonstrates the correspondence between experiment and theory of the charmonium spectrum for two selected models [2]. The dashed lines illustrate theoretically predicted masses, overlaid with black solid lines indicating the well-established experimental results, and red and blue solid lines for recently discovered resonances yet to be incorporated into the model. In the case of the well-established states, there is very good agreement between the theory and experiment. The series of newly discovered charmonium-like states will be the primary focus of this paper.

I will concentrate on results obtained at the BaBar and Belle B-factories. The BaBar results are based on 200–350 fb^{-1} of e^+e^- collisions at the $\Upsilon(4S)$ resonance ($\sqrt{s} \approx 10.58$ GeV) at the PEP-II linear accelerator at SLAC. The Belle results are from up to ≈ 700 fb^{-1} of the same type of collisions at the KEK-B accelerator at KEK.

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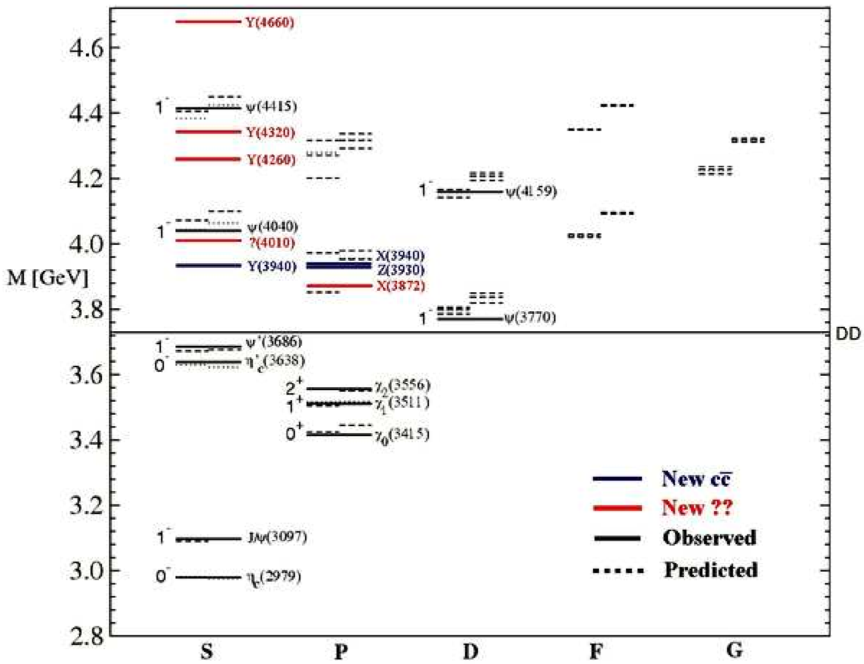

Fig. 1. The charmonium spectrum [2].

2. $X(3872)$

In 2003, Belle discovered a signal in the decay $B^+ \to XK^+$, $X \to J/\psi\pi^+\pi^-$ [3]. This state was found to have a mass of $m_X = 3871.2 \pm 0.6$ MeV/c^2 and a very narrow width, $\Gamma < 2.3$ MeV. This discovery was later verified by CDF, DØ, and BaBar [4]. Evidence for $X \to \gamma J/\psi$ determines C-parity to be positive [5]. Angular analyses from Belle and CDF [6] favour $J^{\rm PC} = 1^{++}$. No charged partners of the $X(3872)$ have been found, and decays to $\chi_{c1,2}\gamma$ and $J/\psi\eta$ have not been seen.

The $X(3872)$ displays some characteristics of a charmonium-like state, but its narrow width above the $D\overline{D}$ threshold, mass, and quantum numbers do not correspond with charmonium model predictions. It is important to consider $m_X \approx m_D + m_{\overline{D}^{*0}}$, leading to speculation that the $X(3872)$ may be the bound state of two D mesons, *i.e.* a $D^0\overline{D}^{*0}$ molecule. This is supported by predictions for its mass, decay modes, $J^{\rm PC}$ values, and branching fractions. Other more exotic interpretations include tetraquark, glueball, or charmonium-gluon hybrid bound states. For a summary of theoretical interpretations of the $X(3872)$, see [7].

3. $X(3940)$, $Y(3930)$, $Z(3940)$

Belle has discovered three more charmonium-like states in a similar mass range via distinct production methods and decay modes. All three states have plausible charmonium model interpretations [8].

The $X(3940)$ was discovered by the recoil of the J/ψ in the double-charmonium production of $e^+e^- \to J/\psi X(3940)$ on 350 fb^{-1} of data [9]. It was found to decay to DD^* but not DD. This points towards an assignment as the $\eta_c(3S)$.

The $Y(3930)$ was seen in the decay $B \to KY$, $Y \to J/\psi\omega$. In Belle's dataset of 278M B decays, they measured a mass and width of $m_Y = 3943 \pm 11 \pm 13$ MeV$/c^2$ and $\Gamma(Y) = 87 \pm 22 \pm 26$ MeV [10]. This state was confirmed by BaBar [11], but using 385M B decays they measured it to have a mass and width of $m_Y = 3914.3^{+3.8}_{-3.4} \pm 1.6$ MeV$/c^2$ and $\Gamma(Y) = 33^{+12}_{-8} \pm 1$ MeV. An apparent interpretation of the $Y(3930)$ state is the $\chi_{c1}(2P)$ charmonium state.

Finally, using 395 fb^{-1} of data, the $Z(3930)$ was found by Belle in the two-photon process $\gamma\gamma \to Z(3930)$ and decaying to $D\overline{D}$ [12]. The $\chi_{c2}(2P)$ charmonium assignment is an eminent choice based on its production, decay, mass, and width.

4. States produced in ISR

Several new states have been discovered via initial-state-radiation production. The first of these was BaBar's discovery [13] of a broad structure in the decay $e^+e^- \to Y(4260)$, $Y(4260) \to J/\psi\pi^+\pi^-$. Based on 211 fb^{-1} of data, the mass and width of this bump were measured to be $m_Y = 4259 \pm 8^{+2}_{-6}9$ MeV$/c^2$ and $\Gamma(Y) = 88 \pm 23^{+6}_{-4}$. Following this discovery, CLEO performed a centre-of-mass energy scan and collected data directly at the $Y(4260)$ resonance [14]. Reconstructing 16 decay modes, they confirmed BaBar's discovery as well as finding evidence for $Y(4260) \to J/\psi\pi^0\pi^0$ and $Y(4260) \to J/\psi K^+K^-$. Using 550 fb^{-1} of data, Belle has also confirmed BaBar's discovery [15], measuring a mass of $m_Y = 4247 \pm 12^{+17}_{-26}$ MeV$/c^2$ and a width of $\Gamma(Y) = 108 \pm 19^{+8}_{-10}$ MeV. Additionally, Belle claims a second much broader resonance at $m = 4008 \pm 40^{+72}_{-28}$ MeV$/c^2$ with a width of $\Gamma = 226 \pm 44^{+87}_{-79}$ MeV. Because these states are produced in the annihilation of e^+e^-, they necessarily have $J^{\mathrm{PC}} = 1^{--}$. However, all of the 1^{--} charmonium states have already been accounted for.

This difficulty was compounded when BaBar's search for an accompanying $Y(4260) \to \psi(2S)\pi^+\pi^-$ decay with 298 fb^{-1} of data turned up a structure at a higher mass that is incompatible with the $Y(4260)$. This new state was found to have a mass of $m_Y = 4324 \pm 24$ MeV$/c^2$ and a width of $\Gamma(Y) = 172 \pm 33$ MeV [16]. Belle confirmed this discovery on 670 fb^{-1} of data, measuring $m_Y = 4361 \pm 9 \pm 9$ MeV/c^2 with a width of $\Gamma(Y) = 74 \pm 15 \pm 10$ MeV, while finding further evidence for a higher resonance with a mass of $m_Y = 4664 \pm 11 \pm 5$ MeV/c^2 and width of $\Gamma(Y) = 48 \pm 15 \pm 3$ MeV [17]. These findings now overpopulate 1^{--} by four states, making it impossible to explain these resonances within the charmonium model.

5. Conclusion

The charmonium model has had great success, but recent experimental results from the B-factories is challenging our understanding of the strong force. It is clear that the $X(3872)$ is not a charmonium state; it is likely a $D^0\overline{D}^{*0}$ molecule. The nature of the ISR-produced 1^{--} states is unclear. Going beyond the charmonium model, lattice QCD and NRQCD will begin to take the lead in the search for a theoretical interpretation. On the experimental front, the BaBar, Belle, and CLEO experiments will remain operational through 2008, followed by the upgraded BES-III thereafter. In the longer term, a Super B-factory collaboration offers the possibility of more than an order of magnitude increase in data. This is indeed a very exciting time in the field of quarkonium physics.

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