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 $3.93 \text{ GeV}/c^2$, and four new resonances in initial state radiation (ISR) decays.

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 talk.

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

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 $m_X = 3871.2 \pm 0.6 \text{ MeV}/c^2$ and a very narrow width, $\Gamma < 2.3 \text{ MeV}$. This discovery was later
Fig. 1. The charmonium spectrum \[2\].

verified by CDF, D0, and BABAR \[4\]. Evidence for \(X \rightarrow \gamma J/\psi\) determines C-parity to be positive \[5\]. Angular analyses from Belle and CDF \[6\] favour \(J^{PC} = 1^{++}\). 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 \(D\bar{D}\) threshold, mass, and quantum numbers do not correspond with charmonium model predictions. It is important to consider \(m_X \approx m_D + m_{D^*}\), leading to speculation that the \(X(3872)\) may be the bound state of two \(D\) mesons, i.e. a \(D^0\bar{D}^{*0}\) molecule. This is supported by predictions for its mass, decay modes, \(J^{PC}\) 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 \(J/\psi\) in the double-charmonium production of \(e^+e^- \rightarrow J/\psi X(3940)\) 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 $B \rightarrow KY$, $Y \rightarrow J/\psi\omega$. 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 $m_Y = 3943^{+3.4}_{-3.8} \pm 1.6$ 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 $\gamma\gamma \rightarrow Z(3930)$ and decaying to $D\bar{D}$ [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 $e^+e^- \rightarrow Y(4260)$, $Y(4260) \rightarrow J/\psi\pi^+\pi^-$. Based on 211 fb$^{-1}$ of data, the mass and width of this bump were measured to be $m_Y = 4259 \pm 8^{+2}_{-6}$ MeV/$c^2$ and $\Gamma(Y) = 88 \pm 23^{+6}_{-4}$ MeV. 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 $Y(4260) \rightarrow J/\psi\pi^0\pi^0$ and $Y(4260) \rightarrow J/\psi K^+K^-$. 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 $\Gamma(Y) = 108 \pm 23^{+8}_{-10}$ 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 $J^{PC} = 1^{--}$. However, all of the $1^{--}$ charmonium states have already been accounted for.

This difficulty was compounded when BABAR’s search for an accompanying $Y(4260) \rightarrow \psi(2S)\pi^+\pi^-$ 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 $D^0\bar{D}^0$ 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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