EXOTIC HADRON SPECTROSCOPY

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This review is focused on recent BaBar and Belle results on the quarkonium-like states.

1 Introduction

For many long years the physics of quarkonium remained a seemingly well-understood field, where as was believed the theory described experimental data quite reliably. Over the past few years a new era of charmonium physics began thanks to numerous surprising results obtained mostly in the BaBar and Belle experiments at B-factories, where huge collected integrated luminosity is combined together with various mechanisms of charmonium production. Since 2002, more than ten new states containing the $c\bar{c}$ pair have been observed. Only three of them (h_c, η_c' and χ_{c2}') are identified as possible candidates for charmonium excitations. For the others the term 'charmonium-like' state was introduced, addressing the presence of $c\bar{c}$ pair, but stressing that their properties are poorly consistent with those expected by the charmonium model. This review presents the recent results on the newly observed X, Y and Z charmonium-like states and their probable counterparts in the $s\bar{s}$ and $b\bar{b}$ sectors.

2 X(3872)

The first enigmatic state, the $X(3872)$, was discovered in 2003 by Belle [1] in the $\pi^+\pi^- J/\psi$ invariant mass spectrum from $B^+ \to K^+\pi^+\pi^- J/\psi$ decays. The narrow peak ($\Gamma < 2.3\,$Mev at 90% CL) appeared exactly at the $D^0\bar{D}^{*0}$ threshold. This state was soon confirmed by CDF [2], D0 [3] and BaBar [4]. All experiments observed the $\pi^+\pi^-$ system tends to the kinematic limit as if the decay proceed via the isospin-violating $\rho J/\psi$ mode. The observation of radiative transitions to both $\gamma J/\psi$ and $\gamma\psi'$ [5,6] confirmed that the $\pi^+\pi^-$ system has quantum numbers of ρ-meson, thus the observation decay mode is indeed isospin-violating. An angular analysis [7] led to the conclusion that the only possible J^{PC} assignments for the $X(3872)$ are 1^{++} and 2^{-+}.

Two yet undiscovered charmonium states, χ_{c1}' and η_{c2}, correspond to the possible $X(3872)$ quantum numbers. However, the measured $X(3872)$ parameters and decays pattern do not match both assignments. An interpretation of the $X(3872)$ as tetraquark state [8] suggests the existence of another neutral and two charged $X(3872)$-partners with similar masses. BaBar found no evidence for a signal of the X^- in $B \to K\pi^-\pi^0 J/\psi$ decays [9]. In search for the neutral partner, both BaBar [10] and Belle [11] measured the $X(3872)$ mass for $B^+ \to K^+\pi^+\pi^- J/\psi$ and $B^0 \to K_S^0\pi^+\pi^- J/\psi$ decays separately and found mass differences to be consistent with zero. These ruled out a tetraquark hypothesis for the $X(3872)$.

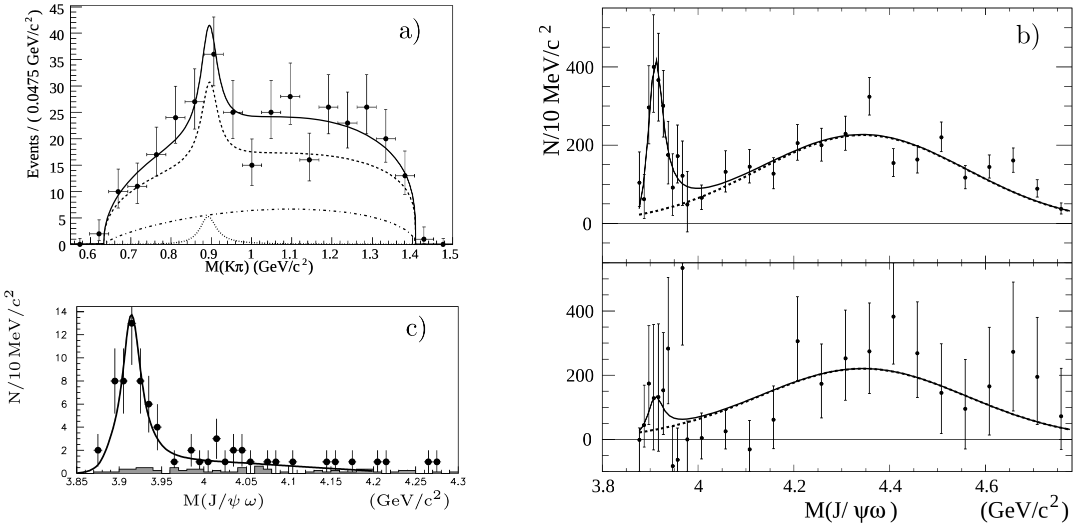

Figure 1: The $K\pi$ mass spectra in $B \to K\pi X(3872)$ decays (Belle). The $\omega J/\psi$ mass spectra (b) in $B \to K\omega J/\psi$ (BaBar) (c) in $\gamma\gamma \to \omega J/\psi$ (Belle).

An intriguing $X(3872)$ feature is the proximity of its mass to the $D^0\bar{D}^{*0}$ threshold, which has stimulated many papers interpreting the $X(3872)$ as a molecule-like system of a D^0 and $\bar{D}^{*0}$, bound by light hadrons exchange [12]. The molecular interpretation meets some difficulty to explain both prompt production in $p\bar{p}$ interaction of such friable object and the J/ψ formation in its decay. A general idea to resolve this is to assume the presence of χ'_{c1} admixture in the $X(3872)$ wave function, which responsible for its production and decay. Therefore it is interesting to compare dynamics of the $X(3872)$ production in B-decays with that of χ_{c1}, *e.g.* in three-body $B \to K\pi X(3872)$ decays. Such a study was reported by Belle in 2008 [11]. It is evident from the $K\pi$ mass spectrum (Fig. 1a) that the $K\pi$ pairs have a phase space-like distribution, with almost no K^* signal. For all of the known charmonium states the K^* dominates in the $K\pi$ system.

3 Y(3940)

In 2005, Belle reported observations of three states with masses near 3940 MeV: the near-threshold $\omega J/\psi$ mass peak, called $Y(3940)$, in the decay $B \to K\omega J/\psi$ [13]; the $X(3940)$, seen in the process $e^+e^- \to J/\psi D\bar{D}^*$ in the $D\bar{D}^*$ mass spectrum [14]; and the $Z(3930)$ seen in $\gamma\gamma$ events and decaying into $D\bar{D}$ [15]. Only the last state was convincingly assigned to the charmonium level χ'_{c2}. In spite of the conventional decay mode, the $X(3940)$ assignment to charmonium excitation is complicated, as the unfilled 0^{-+} state (expected in the studied reaction), η''_c, is supposed to be significantly heavier. The first state, the $Y(3940)$, is the most mysterious: while its mass is well above the thresholds for decays to $D\bar{D}$ or $D\bar{D}^*$ final states, its decays to neither of these modes were observed. While the decay to the first final state can be forbidden by parity conservation, the second decay should dominate for charmonium with such mass.

In 2008, BaBar presented a study of $B \to K\omega J/\psi$ [16]. In their analysis a peak in the $\omega J/\psi$ mass spectrum is qualitatively agrees with the Belle's result (Fig. 1b), however, the BaBar values for mass and width are lower than the corresponding Belle's values: $M = 3914^{+3.8}_{-3.4} \pm 1.6$ MeV, and $\Gamma = 33^{+12}_{-8} \pm 0.6$ MeV. In 2010, Belle reported on observation of a peak in the cross section for $\gamma\gamma \to \omega J/\psi$ [17], called $X(3915)$. The mass and width of the peak in the $\omega J/\psi$ mass spectrum (Fig. 1c) are well consistent with those reported for the $Y(3940)$ by BaBar. The common observation decay mode and similar parameters suggest that the $X(3915)$ and $Y(3940)$ are the same state.

In the absence of the information on quantum numbers it is difficult to find a charmonium assignment for this state. But even more problematic for accommodation of this state as char-

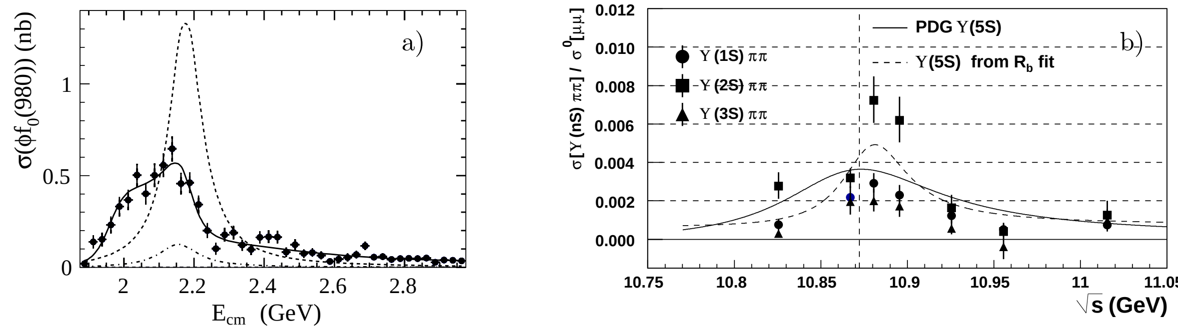

Figure 2: The cross sections for the processes a) $e^+e^- \to \eta\phi f_0$, b) $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ at Belle.

monium is the large $\omega J/\psi$ partial width. It can be roughly estimated assuming the $B \to KY$ decay branching fraction does not exceed 10^{-3}, typical for two-body B-decays into charmonium states. Using the measured product of branching fractions $\mathcal{B}(B \to KY)\mathcal{B}(Y \to \omega J/\psi)$ and the $Y(3940)$ full width, such an estimate gives $\Gamma(Y \to \omega J/\psi$ of a few MeV. If similar estimates applied for $\gamma\gamma \to X(3915)$ assuming $\Gamma_{\gamma\gamma} \sim 1\,\mathrm{keV}$, typical for charmonium, we find $\Gamma(X(3915) \to \omega J/\psi) \sim 1\,\mathrm{MeV}$. In both cases the estimated values are at least an order of magnitude higher than typical width of charmonium transitions via light hadrons.

4 The charged and strange charmonium-like states

The evidence of the first charged charmonium-like state, $Z(4430)^+$, seen as a peak in the $\pi^+\psi'$ invariant mass spectrum from $B \to K\pi^+\psi'$ decays was reported by Belle [18] in 2008. After BaBar did not confirm the $Z(4430)^+$ peak in their study of $B \to K\pi^+\psi'$ decays [19], Belle reanalysed their data using Dalitz plot technique and confirmed that the observed peak is not a reflection from interfering resonances in the $K\pi$ channel [20]. Besides the $Z(4430)^+$, Belle observed also two resonant states in the $\pi^+\chi_{c1}$ system [21] with the Dalitz analysis of $B \to K\pi^+\chi_{c1}$ decays.

In 2009, CDF presented an evidence for the narrow near-threshold resonance, called $Y(4140)$, in $\phi J/\psi$ system from $B^+ \to K^+\phi J/\psi$ decays [22] with mass $4143.0 \pm 2.9 \pm 1.2\,\mathrm{MeV}$ and width $11.7^{+8.3}_{-5} \pm 3.6\,\mathrm{MeV}$. Belle searched for this state using the same process and found no significant signal [23]. Although the upper limit on the production rate obtained by Belle is lower than the central value of the CDF measurement, Belle result does not contradict with CDF's observation taking into account the large errors. Belle also performed a search for this state in $\gamma\gamma$ fusion, motivated by $D_s^{*+}D_s^{*-}$-molecule interpretation for the $Y(4140)$. While a signal for the $Y(4140)$ is not observed, evidence for another narrow structure at 4350MeV in the $\phi J/\psi$ spectrum is reported with significance of $\sim 3.2\sigma$. Taking into account small significances of both CDF's and Belle's peaks, these states need further confirmation.

5 The 1^{--} quarkonium-like states

In 2005, using the ISR process BaBar studied the cross section for $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} \sim 4\,\mathrm{GeV}$ and discovered a broad peak near $4260\,\mathrm{MeV}$ [24]. This state was confirmed by CLEO [25] and Belle [26]. A year after BaBar reported on a similar structure in the cross section for $e^+e^- \to \pi^+\pi^-\psi'$ but at mass $\sim 60\,\mathrm{MeV}$ higher [27]. Belle confirmed this observation, but in addition found that the structure is formed from two narrower peaks [28]. Unusual decay modes and lack of vacant charmonium levels make the charmonium assignments for these three states very unlikely.

The similar states containing $s\bar{s}$ pair was searched by BaBar in the ISR process in $\phi\pi^+\pi^-$ final state. Two clear structures near $\sqrt{s} = 1680$ and $2175\,\mathrm{MeV}$ were observed; the former is likely the $\phi(1680)$ state, while the latter was produced predominantly via a ϕf_0 intermediate state, and called $Y(2175)$ [29]. BES confirmed this state in the ϕf_0 invariant mass spectrum of $J/\psi \to \eta\phi f_0$ decays [30]. In the subsequent Belle study [31] this state is also clearly seen (Fig: 2a). However, the widths of the $Y(2175)$ tends to be larger than in previous measurements, that may suggest that it is an excited 1^{--} $s\bar{s}$ state, rather than $s\bar{s}$ counterpart of $Y(4260)$.

In 2008, Belle has reported the observation of enhanced $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, and $\Upsilon(3S)\pi^+\pi^-$ production at the range of $\sqrt{s}$ between 10.83 and 11.02 GeV [32]. The energy-dependent cross sections for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ events were found to differ from the shape of the $e^+e^- \to b\bar{b}$ cross section (Fig. 2b).

6 Summary

The number of quarkonium-like states continues to grow. However, today none of the traditional or exotic theoretical models are able to simultaneously explain the variety of their properties.

References

1. S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **91**, 262001 (2003).
2. D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **93**, 072001 (2004).
3. V.M. Abazov *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **93**, 162002 (2004).
4. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev.* D **71**, 071103 (2005).
5. K. Abe *et al.* (Belle Collaboration), hep-ex/0505037 (2005).
6. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **102**, 132001 (2009).
7. A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **98**, 132002 (2007).
8. See, for example: L. Maiani *et al. Phys. Rev.* D **71**, 014028 (2005).
9. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev.* D **71**, 031501 (2005).
10. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev.* D **77**, 111101 (2008).
11. I. Adachi *et al.* (Belle Collaboration), arXiv:0809.1224 (2008).
12. See, for example: F.E. Close and P.R. Page, *Phys. Lett.* B **578**, 119 (2004).
13. S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **94**, 182002 (2005).
14. K. Abe *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **98**, 082001 (2007).
15. S. Uehara *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **96**, 082003 (2006).
16. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **101**, 082001 (2008).
17. S. Uehara *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **104**, 092001 (2010).
18. S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **100**, 142001 (2008).
19. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev.* D **79**, 112001 (2009).
20. R. Mizuk *et al.* (Belle Collaboration), *Phys. Rev.* D **80**, 031104 (2009).
21. R. Mizuk *et al.* (Belle Collaboration), *Phys. Rev.* D **78**, 072004 (2008).
22. A. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **102**, 242002 (2009).
23. C. Z. Yuan (for the Belle Collaborations), arXiv:0910.3138 (2009).
24. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **95**, 142001 (2005).
25. T. Coan *et al.* (CLEO Collaboration), *Phys. Rev. Lett.* **96**, 162003 (2006).
26. C.-Z. Yuan *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **99**, 182004 (2007).
27. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. Lett.* **98**, 212001 (2007).
28. X.-L. Wang *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **99**, 142002 (2007).
29. B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev.* D **74**, 091103 (2007).
30. M. Ablikim *et al.* (BES Collaboration), *Phys. Rev. Lett.* **100**, 102003 (2008).
31. C.P. Shen *et al.* (Belle Collaboration), *Phys. Rev.* D **80**, 031101 (2009).
32. K.-F. Chen *et al.* (Belle Collaboration), arXiv:0808.2445 (2008).