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EXOTIC/CHARMONIUM HADRON SPECTROSCOPY AT BELLE AND BABAR

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Abstract

A brief review of experimental results on charmonium and charmonium-like hadron spectroscopy at B-factories is presented. A special focus is put on recent results of η_c and $\eta_c(2S)$ study, $X(3872)$ radiative decays, $\omega J/\psi$ final state study and search for charmonium production in radiative Υ decays.

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I. CONVENTIONAL AND "EXOTIC" CHARMONIUM STATES

The first charmonium state J/ψ was discovered in 1974 [1]. Then in six years nine more $(c\bar{c})$ states were observed. No new states were found during next 22 years, until in 2002 Belle reported the detection of $\eta_c(2S)$ [2]. In 2003 Belle discovered $X(3872)$ [3], which marked the beginning of "exotic", or unconventional charmonium-like states era. Such states decay in ways, peculiar to usual charmonium, but have masses, widths, quantum numbers and decay ratios, which can hardly be explained by the classical quark-parton model. Since then two conventional and more than dozen "exotic" charmonium states were reported. Comprehensive review of their characteristics, possible explanations etc can be found in [4]. In this paper we report some recent experimental results on this topic from B-factories.

II. η_c AND $\eta_c(2S)$

Although η_c and $\eta_c(2S)$ have been around for some time and studied by different experiments, there is still large spread in their mass and width measurements [5]. Moreover, our knowledge of hadronic decays of these charmonia is rather poor. Both Belle and BaBar performed recently new measurements of η_c and $\eta_c(2S)$ characteristics.

BaBar claimed that $\gamma\gamma \to \eta_c \to K_S K^{\pm}\pi^{\mp}$ is the "right place" for such study since Breit-Wigner line shape is appropriate approximation here [6]. With data set of $469\,\mathrm{fb}^{-1}$ mass and width of η_c were measured relative to J/ψ. In the same paper transition form factor in $\gamma\gamma \to \eta_c$ decay was measured and nice agreement with pQCD was observed. BaBar also reported mass and width measurement of $\eta_c(2S)$ in the same production process [7].

Belle took another approach. They studied $B^{\pm} \to K^{\pm}\eta_c(\eta_c(2S))$, $\eta_c(\eta_c(2S)) \to (K_S K\pi)^0$ decay chain and consistently took into account interference between decay under study and nonresonant decay into the same final state [8]. Results, obtained with and without interference are quite different, which means that taking it into account is important.

Until recently only one decay mode of $\eta_c(2S)$ was known, $\eta_c(2S) \to (K_S K\pi)^0$. Decays to 4-prong final state have not been observed [9]. Belle with $923\,\mathrm{fb}^{-1}$studied decays to 6-prong final states: 6π, $2K4\pi$, $4K2\pi$, $K_SK3\pi$ [10]. $\eta_c(2S)$, as well as χ_{c0} and χ_{c2}, were clearly seen in 6π, $2K4\pi$, and $K_SK3\pi$ distributions. BaBar looked at $K^+K^-\pi^+\pi^-\pi^0$ invariant mass spectrum from $\gamma\gamma$ process and found $\eta_c(2S)$ signal, as well as η_c, χ_{c0} and χ_{c2} [7].

III. $X(3872)$ RADIATIVE DECAYS

The $X(3872)$ was discovered by Belle as a narrow peak in $J/\psi\pi^+\pi^-$ invariant mass from $B^\pm \to J/\psi\pi^+\pi^-K^\pm$ decays [3]. It was confirmed by CDF [11], D0 [12] and BaBar [13]. Among newly observed "exotic" charmonium-like states $X(3872)$ is the most studied one. It has very small width $\Gamma < 2.3\,\text{GeV}$ at 90% CL for a state above open charm threshold. Its mass is very close to D^0D^{*0} threshold, $M(X(3872)) - (m_{D^0} + m_{D^{*0}}) = -0.32 \pm 0.35\,\text{GeV}$. In decays to $J/\psi\pi^+\pi^-$ invariant mass of $\pi\pi$ pair is consistent with originating from $\rho \to \pi^+\pi^-$, indicating $C = +1$ parity of $X(3872)$. Since all charmonia are isospin singlets, decays to $J/\psi\rho$ violate isospin and should be strongly suppressed. CDF studied angular distributions in $X(3872) \to J/\psi\pi^+\pi^-$ decay and concluded that possible J^{PC} assignments for $X(3872)$ are 1^{++} and 2^{-+} [14].

There are several unoccupied charmonium levels with appropriate quantum numbers but their predicted masses are either too high (χ'_{c1}, $J^{PC} = 1^{++}$) or too low (η_{c2}, $J^{PC} = 2^{-+}$). The whole set of $X(3872)$ characteristics also makes it hard to describe $X(3872)$ as a conventional charmonium. Proximity of $X(3872)$ mass to D^0D^{*0} threshold led to a suggestion, that it may be a molecule-like D^0D^{*0} bound state [15].

Weighty argument in distinguishing between different possibilities are radiative decays $X(3872) \to \gamma\psi'$ and $X(3872) \to \gamma J/\psi$. If $X(3872)$ is a charmonium state χ'_{c1}, partial with of $X(3872) \to \gamma\psi'$ decay should be larger than that of $X(3872) \to \gamma J/\psi$ by more than factor of ten [16]. In case of molecular state or η_{c2} the situation is reversed and $\gamma J/\psi$ mode is favoured [17, 18].

The first evidence for $X(3872) \to \gamma J/\psi$ by Belle was based on $256\,\text{fb}^{-1}$ with 13.6 ± 4.4 events [19] and was confirmed by BaBar on $424\,\text{fb}^{-1}$ with 23.0 ± 6.4 events [20]. Observation of this channel confirmed even parity of $X(3872)$. In 2009 BaBar reported evidence of $X(3872) \to \gamma\psi'$ based on $424\,\text{fb}^{-1}$ with 25.4 ± 7.4 signal events ($3.6\,\sigma$) [21] (see Fig. 1, (a)). The signal yield implied $\mathcal{B}(X(3872) \to \gamma\psi')/\mathcal{B}(X(3872) \to \gamma J/\psi) = 3.4 \pm 1.4$. However in 2010 Belle based on a larger sample $711\,\text{fb}^{-1}$ found no evidence for $X(3872) \to \gamma\psi'$ (see

Fig. 1, (b), (c)), while $\gamma J/\psi$ mode was observed at a rate that agrees with BaBar [22]. Belle set a 90% CL upper limit on the $\gamma\psi'/\gamma J/\psi$ ratio of < 2.0.

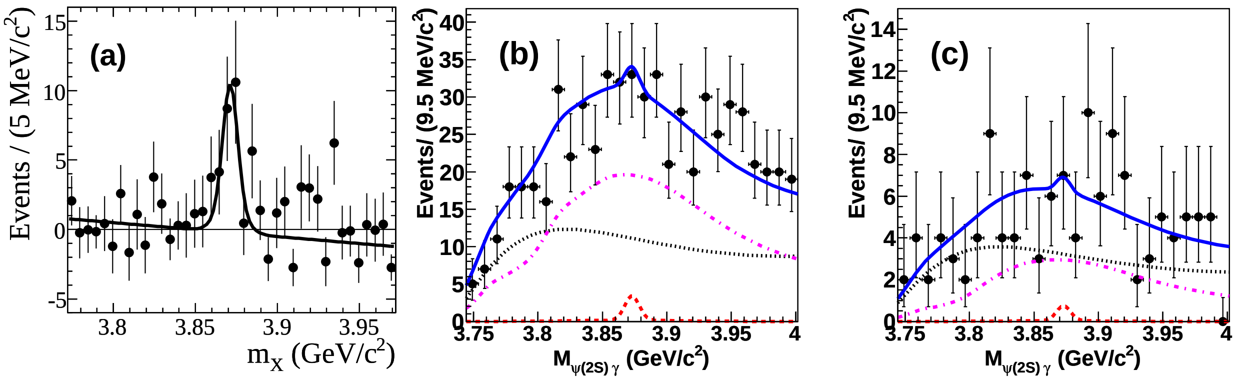

FIG. 1: The $\gamma\psi'$ invariant mass distribution for (a) $B^+ \to \gamma\psi' K^+$ from BaBar, obtained by fit in bins, (b) $B^+ \to \gamma\psi' K^+$ and (c) $B^0 \to \gamma\psi' K^0$ from Belle.

IV. STUDY OF $\omega J/\psi$ FINAL STATE

Three states with masses close to 3940 MeV were found: $X(3940)$ [23], $Y(3940)$ [24] and $Z(3930)$ [25], the latter usually identified with χ'_{c2}. These three states are considered to be distinct particles, though there is no decisive evidence for this. $Y(3940)$ mass is well above DD and DD^* thresholds, but the partial width of decay to hidden charm is unexpectedly large: $\mathcal{B}(Y \to \omega J/\psi)/\mathcal{B}(Y \to D^0 D^{*0}) > 0.71$ [26].

Belle studied untagged two-photon process $\gamma\gamma \to \omega J/\psi$ with 694 fb^{-1} of data, collected at $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(5S)$ resonances. A state with $M = 3915 \pm 4$ MeV and $\Gamma = 17 \pm 11$ MeV was found [27], compatible with $Y(3940)$. If it is so, it narrows its quantum numbers J^{PC} to $0^{\pm+}$ or $2^{\pm+}$. Measured partial width $\Gamma_{\gamma\gamma}\mathcal{B}(Y \to \omega J/\psi) = 61 \pm 19$ eV (for 0^{++}). If $\Gamma_{\gamma\gamma} \sim \mathcal{O}(1\,\text{keV})$, a typical value for charmonium, then $\Gamma(Y \to \omega J/\psi) \sim \mathcal{O}(1\,\text{MeV})$, which is very large for a hadronic inter-charmonium transition.

Though mass of $X(3872)$ is too small for decay to $\omega J/\psi$, in some models it may decay to low-mass tail of the ω and J/ψ with a rate, comparable to decay $X(3872) \to \pi\pi J/\psi$ [18]. In 2005 Belle reported an evidence for subthreshold decay $X(3872) \to \omega J/\psi$, consistent with the prediction [19]. In 2008 BaBar studied B-decay $B^+ \to \pi\pi\pi^0 J/\psi K^+$ and in mass distribution of $\pi\pi\pi^0 J/\psi$ observed $Y(3940)$, but did not find $X(3872)$ [28]. In 2010 BaBar remade this analysis with $433\,\mathrm{fb}^{-1}$ and lower requirement on $\pi\pi\pi^0$ invariant mass loosened from $0.7695\,\mathrm{GeV}$ to $0.7400\,\mathrm{GeV}$. Both $Y(3940)$ and $X(3872)$ were observed with masses and widths, consistent with previous measurements. BaBar also investigated the shape of $\pi\pi\pi^0$ invariant mass distribution for selected $X(3872) \to \omega J/\psi$ events. They found that it favours P-wave description by $1.5\,\sigma$ ($\chi^2/\mathrm{NDF} = 10.17/5$ for S-wave, $\chi^2/\mathrm{NDF} = 3.53/5$ for P-wave), which indicates $J^P = 2^-$ for $X(3872)$, which thus may be interpreted as η'_{c2} charmonium state. However, possible interference between different decays, contributing to $\pi\pi\pi^0 J/\psi$ final state, was not taken into account, and explanation of significant rate of $X(3872) \to D\bar{D}\pi$ would be a challenge for η'_{c2} [29].

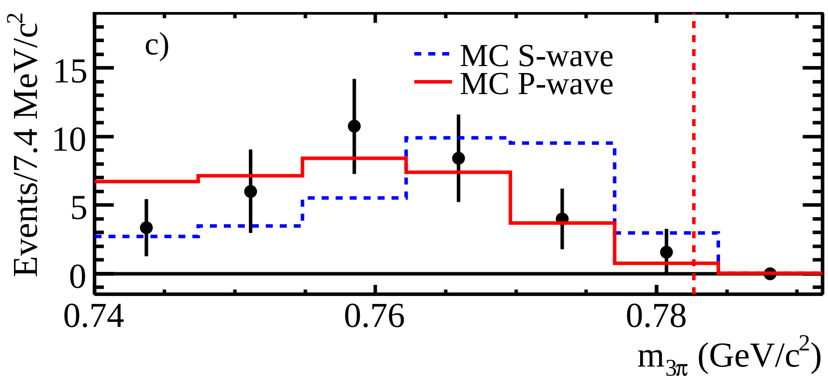

FIG. 2: The $\pi^+\pi^-\pi^0$ invariant mass distribution for $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ decays from BaBar.

V. SEARCH FOR CHARMONIUM PRODUCTION IN RADIATIVE Υ DECAYS

Belle used its extensive data set, collected at $\Upsilon(1S)$ resonance, to investigate $b\bar{b} \to c\bar{c}\gamma$ transitions [30]. Calculation predicts $\sim 10^{-6}$ decay rates for lowest lying P-wave spin-triplet (χ_{cJ}, $J = 0, 1, 2$) and $\sim 5 \times 10^{-5}$ for S-wave spin-singlet state η_c [31]. No prediction exists for allowed excited or "exotic" states, like $X(3872)$. The photon detection required $E_\gamma^{lab} > 3.5\,\mathrm{GeV}$, which corresponded to $4.8\,\mathrm{GeV}$ mass of a particle, produced in $\Upsilon(1S)$ radiative decay. Initial state radiation (ISR) was removed by requirement on photon polar angle. ISR production of ψ' in $\pi^+\pi^- J/\psi$ channel was used as a cross-check, and the cross section for this process was determined as $20.2 \pm 1.1\,\mathrm{pb}$, in agreement with theoretical calculation. One event was observed in the signal region of $X(3872)$, which corresponds to upper limit $\mathcal{B}(\Upsilon(1S) \to \gamma X(3872)) \times \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 2.2 \times 10^{-6}$ at 90% CL. Furthemore, no evidence for excited charmonium states below $4.8\,\mathrm{GeV}$ was found.

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