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Study of Quarkonia and Quarkonium-like States at Belle

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We review recent results on quarkonia and quarkonium-like states from the Belle experiment. An enhancement of the transition $\Upsilon(4S) \to \eta\Upsilon(1S)$ with respect to the transition $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$ is confirmed. The first observation of the processes $e^+e^- \to \eta\Upsilon_J(1D)$ in e^+e^- annihilation near $\Upsilon(5S)$ and $\Upsilon(4S) \to \eta'\Upsilon(1S)$ is reported. The new state $X^*(3860)$ is clearly observed with a significance of 6.5σ in the distribution of invariant mass of $D\bar{D}$. We search for charmonium-like states, including $X(3872)$ in the missing mass spectrum of K^+, $Y(4660)$ and its spin partner in the distribution of $\Lambda_c^+\Lambda_c^-$ invariant mass, and double Z_c in $\Upsilon(1S,2S)$ decays and e^+e^- annihilation at $\sqrt{s} = 10.52$, 10.58, and 10.867 GeV. No significant signals are observed in any of the studied modes, and the 90% confidence level (C.L.) upper limits on their branching fractions or the Born cross sections are determined.

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1. Introduction

The total integrated luminosity of B factories reached 1040 fb^{-1} [1]. Considerable research efforts have been devoted to the study of quarkonia and quarkonium-like States using rich data samples taken in the $\Upsilon(1S,2S,3S,4S,5S)$ resonances. Bottomonium spectroscopy was gradually developed by the study of transitions between its states. The charmonium-like states have been intensively investigated in the B decays, and initial state radiation (ISR) and two-photon processes at Belle. The bottomonium-like states, including $Z_b(10610)$ and $Z_b(10650)$ are now quite well known objects thanks to Belle studies. In this review, the transitions between bottomonium states and the search for some charmonium-like states, e.g., $X(3872)$, $Y(4660)$, etc, are mainly reported.

2. The study of quarkonia at Belle

2.1 The hadronic transition in bottomonium decay

The transitions between bottomonium states via an η meson are predicted in Refs. [2, 3, 4], to be highly suppressed, since they require a spin flip of the heavy quark. However, in experiment, the results are conflicted with those from theoretical predictions. Belle [5] measured the branching fractions $\mathscr{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))$ and $\mathscr{B}(\Upsilon(4S)\to\eta\Upsilon(1S))$, and gave the ratio of branching fractions:

$$\mathscr{R}=\frac{\mathscr{B}(\Upsilon(4S)\to\eta\Upsilon(1S))}{\mathscr{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))}=2.07\pm0.30\pm0.11,$$

where the first uncertainty is statistical, while the second is systematic. These results are consistent with the prior measurements by BABAR [6] within a reasonable error range. They confirmed an enhancement of the transition $\Upsilon(4S)\to\eta\Upsilon(1S)$ with respect to the transition via a dipion. Given the possible $\Upsilon(1^3D_{1,2})$ production through double-radiative transitions from the $\Upsilon(4S)$ through the $\chi_{bJ}(2P)$, the search for the $\Upsilon(1^3D_{1,2})$ were also performed in Ref. [5]. No significant signals are observed, and the upper limits at 90% C.L. on the product of branching fractions are obtained to be $\mathscr{B}(\Upsilon(4S)\to\gamma\gamma\Upsilon(1^3D_{1,2}))\times\mathscr{B}(\Upsilon(1^3D_{1,2})\to\eta\Upsilon(1S))<2.3\times10^{-5}$.

The η transition in higer mass bottomonium spectroscopy, e.g., e^+e^- reaction near the $\Upsilon(5S)$, was studied by Belle [7] as well. In this analysis, only the η is reconstructed by $\gamma\gamma$ and the recoil mass spectrum of η candidates is investigated. The clear $\Upsilon(1D)$ signal could be observed, and the evidence for the $e^+e^-\to\eta\Upsilon(2S)$ transition was reported. However, no hints are found for the signals of $\Upsilon(1S)$, $h_b(1P)$ and $h_b(2P)$. In particular, the branching fraction of $e^+e^-\to\eta\Upsilon(1D)$ is compatible with the prediction via hadronic loop machanism in Ref. [8]. No direct evidence is shown to prove the presence of the three states of the $\Upsilon(1D)$ triplet, which attribute to the limited experimental resolution and the possible mixture of different states of the $\Upsilon(1D)$ triplet.

The kinematically allowed transition $\Upsilon(4S)\to\eta'\Upsilon(1S)$ is excepted to be similarly enhanced as $\Upsilon(4S)\to\eta\Upsilon(1S)$ [9]. Belle [10] searched for the the hadronic transition $\Upsilon(4S)\to\eta'\Upsilon(1S)$ using 496 fb^{-1} data collected at the $\Upsilon(4S)$ resonance. The η' is reconstructed by $\rho^0\gamma$ ($2\pi1\gamma$) and $\pi^+\pi^-\eta$ ($2\pi2\gamma$), with $\eta\to\gamma\gamma$. Figure 1 shows the $\Delta M_{\eta'}$ ($M(\Upsilon(4S))-M(\Upsilon(1S))-M(\eta')$) distribution in mode $2\pi1\gamma$ and $2\pi2\gamma$. From Fig. 1, the clear signals for the transition $\Upsilon(4S)\to\eta'\Upsilon(1S)$ could be observed. The statistical significance of the combined measurement is 5.7σ after considering yield-related systematic uncertainties. Finally, the measured branching fraction is $\mathscr{B}(\Upsilon(4S) \to \eta'\Upsilon(1S)) = (3.43 \pm 0.88(stat.) \pm 0.21(syst.)) \times 10^{-5}$. The first observation of an η' transition between bottomonia present a wide range of possibilities for the further development of bottomonium spectroscopy.

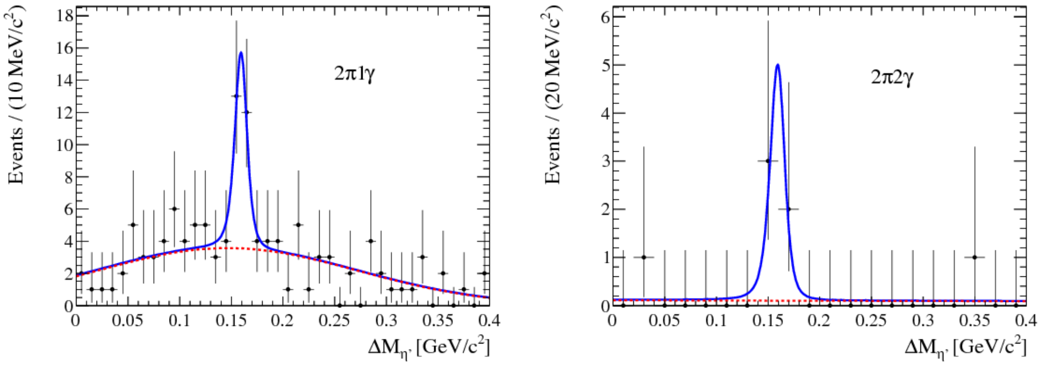

Figure 1: Fit to the $\Delta M_{\eta'}$ distribution for $\Upsilon(4S) \to \eta'\Upsilon(1S)$ candidates reconstructed in the $2\pi 1\gamma$ (left) and $2\pi 2\gamma$ (right) final states. Data are shown as points, the solid blue line shows the best fit to the data, while the dashed red line shows the background contribution.

2.2 An alternative $\chi_{c0}(2P)$ candidate in $e^+e^- \to J/\psi D\bar{D}$

The $\chi_{c2}(2P)$ candidate was observed by Belle [11] and BABAR [12] in the process $\gamma\gamma \to D\bar{D}$. In Ref. [13], the authors show that there is an indication of the $\chi_{c0}(2P)$ with a mass around 3840 MeV and width of about 200 MeV with combined Belle [11] and BABAR [12] data. However, the parameters measured in Ref. [13] are biased, e.g., the $\chi_{c0}(2P)$ mass is shifted to lower values [16]. To search $\chi_{c0}(2P)$ candidate and measure its parameters, Belle [14] presented an updated analysis of the process $e^+e^- \to J/\psi D\bar{D}$ using 1.4 times luminosity greater than the previous analysis [15]. A multivariate method is applied to improve the discrimination of the signal and background events. The distribution of invariant mass of $D\bar{D}$ is shown in Fig. 2, where the new state $X^*(3860)$ is clearly observed with a significance of 6.5σ. An amplitude analysis is performed to study the J^{PC} quantum numbers of the $D\bar{D}$ system. In the default model (constant nonresonant amplitude), exclusion levels of the 2^{++} hypothesis is found to be 3.8σ, and confidence levels of the 2^{++} hypothesis is up to 77%.

2.3 Bottomonium inclusive decays

The χ_{c1} and $f_1(1285)$ productions in $\Upsilon(1S,2S)$ inclusive decays were measured by Belle [17, 18]. The differences in the MC-determined reconstruction efficiencies for different χ_{c1} and $f_1(1285)$ momenta have been considered by partitioning the data samples according to the scaled momentum of χ_{c1} and $f_1(1285)$ in e^+e^- center-of-mass (C.M.) frame. The inclusive branching fractions $\mathscr{B}(\Upsilon(1S) \to \chi_{c1} + anything) = (1.90 \pm 0.43(stat.) \pm 0.14(syst.)) \times 10^{-4}$ is measured with an improved precision over prior measurements [19], and $\mathscr{B}(\Upsilon(2S) \to \chi_{c1} + anything) = (2.24 \pm 0.44(stat.) \pm 0.20(syst.)) \times 10^{-4}$, $\mathscr{B}(\Upsilon(1S) \to f_1(1285) + anything) = (46 \pm 28(stat.) \pm 13(syst.)) \times 10^{-4}$ and $\mathscr{B}(\Upsilon(2S) \to f_1(1285) + anything) = (22 \pm 15(stat.) \pm 63(syst.)) \times 10^{-4}$ are measured for the first time.

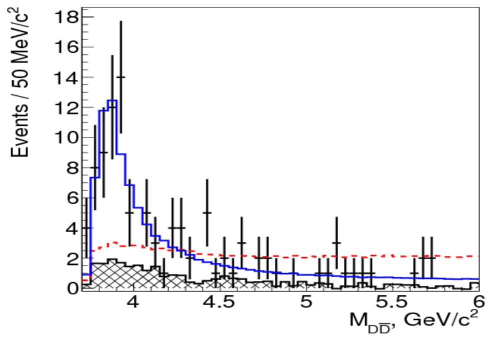

Figure 2: The invariant mass spectrum of $D\bar{D}$ in the $e^+e^- \to J/\psi D\bar{D}$. The points with error bars are the data, the hatched histogram is the background, the blue solid line is the fit with a new resonance $X^*(3860)$ ($J^{PC} = 0^{++}$) and the red dashed line is the fit with nonresonant amplitude only.

Belle [18] performed the measurement of $\chi_{bJ} \to J/\psi + anything$, where the χ_{bJ} is identified through the decay $\Upsilon(2S) \to \gamma\chi_{bJ}$. As shown in Fig. 3 of the spectrum of the $\Upsilon(2S)$ radiative photon energy in the e^+e^- C.M. frame, a clear χ_{b2} signal may be observed with the statistical significances of 3.5σ. For the first time, the $\chi_{b2} \to J/\psi + anything$ branching fraction was reported to be $(1.50 \pm 0.34(stat.) \pm 0.22(syst.)) \times 10^{-3}$. The 90% C.L. upper limits for the $\chi_{b0,b1} \to J/\psi + anything$ branching fractions are set.

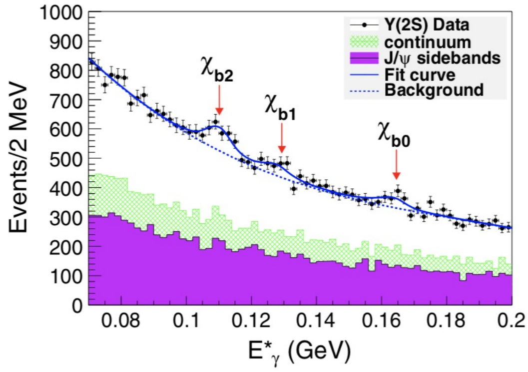

Figure 3: The spectra of the $\Upsilon(2S)$ radiative photon energy in the e^+e^- C.M. frame in $\Upsilon(2S)$ data. The dots with error bars are the $\Upsilon(2S)$ data. The blue solid line is the best fit, and the blue dotted line represents the backgrounds. The magenta shaded histogram is from the normalized J/ψ sideband and the green cross-hatched histogram is from the normalized continuum contributions.

3. The study of quarkonium-like states at Belle

3.1 The absolute branching fractions of $B^+ \to X_{c\bar{c}}K^+$

The discovery of the $X(3872)$ by the Belle collaboration [20] opened a new era in the field of hadron spectroscopy. Considerable efforts in theory have been devoted to interpret $X(3872)$ as tetraquarks, molecules, hybrids, or hadrocharmonia. It is worthwhile mentioning that a measurement of the absolute branching fraction $B^+ \to X(3872)K^+$ is quite useful. For example,

$X(3872)$ [21] is regarded as a mixed molecule-charmonium state when $\mathcal{B}(B^+ \to X(3872)K^+) = (1.00 \pm 0.68) \times 10^{-5}$.

Recently, Belle [22] presented a measurement of $\mathcal{B}(B^+ \to X(3872)K^+)$, along with a simultaneous measurement of the various charmonium(-like) states ($X_{c\bar{c}}$ denotes η_c, J/ψ, χ_{c0}, χ_{c1}, $\eta_c(2S)$, $\psi(2S)$, $\psi(3770)$, and $X(3915)$) that appear in the missing mass spectrum. Fully reconstruction for one of the two charged B measons (B_{tag}) and NeuroBayes neural-network is used to extract the signals and suppress continuum backgrounds throughout this analysis. The signals are identified at the nominal $X_{c\bar{c}}$ mass in the distribution of missing mass: $M_{miss}(K^+) = \sqrt{(p^*_{e^+e^-} - p^*_{tag} - p^*_h)}$/c, where $p^*_{e^+e^-}$, p^*_{tag}, and p^*_h are the four-momenta of the electron-positron initial state, B_{tag}, and K^+, respectively, in the C.M. frame. No significant signal for $X(3872)$ is observed, and the upper limit at 90% C.L. on the $\mathcal{B}(B^+ \to X(3872)K^+)$ is determined to be 2.7×10^{-4}, which is more stringent than that determined by BaBar [23] (3.2×10^{-4}). The 90% C.L. upper limit of $\mathcal{B}(B^+ \to X(3915)K^+) = 2.9 \times 10^{-4}$ is obtained for the first time. The measured branching fractions for η_c and $\eta_c(2S)$ are the most precise to date: $\mathcal{B}(B^+ \to \eta_c K^+) = (12.3 \pm 0.8(stat.) \pm 0.7(syst.)) \times 10^{-4}$ and $\mathcal{B}(B^+ \to \eta_c(2S)K^+) = (4.9 \pm 1.1(stat.) \pm 0.3(syst.)) \times 10^{-4}$.

3.2 $Y(4660)$ and its spin partner

In Refs. [24, 25], the authors predict that the $Y(4660)$ ($f_0(980)\psi'$ bound state) and its spin partner denoted as the Y_η ($f_0(980)\eta_c(2S)$ bound state) have a large partial width into $\Lambda_c^+\Lambda_c^-$. An updated measurement of $B^- \to K^-\Lambda_c^+\Lambda_c^-$ was performed [26] to search the charmonium-like states $Y(4660)$ and Y_η. No clear $Y(4660)$ and Y_η signals is evident in the $M(\Lambda_c^+\Lambda_c^-)$ spectrum. 90% C.L. upper limits on $\mathcal{B}(B^- \to K^-Y)\mathcal{B}(Y \to \Lambda_c^+\Lambda_c^-)$ are determined to be 2.0×10^{-4} and 1.2×10^{-4} for $Y = Y_\eta$ and $Y(4660)$, respectively.

3.3 Double Z_c production in $\Upsilon(1S,2S)$ decays and e^+e^- reactions

In order to understand the nature of Z_c state, the measurements of the process $e^+e^- \to Z_c^+Z_c^-$ is quite useful. For $e^+e^- \to Z_c^+Z_c^-$, the dependence on s (the e^+e^- C.M. energy squared) of the electromagnetic form factor, $F_{Z_c^+Z_c^-}$ is $1/s^3$ for a Z_c state with tetraquark structure or $1/s$ for a Z_c system of two tightly bound diquarks [27, 28]. Very recently, Belle [29] reported the search for Z_c pair production in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays as well as in e^+e^- annihilation at $\sqrt{s} = 10.52$, 10.58, and 10.867 GeV. In the search, the decay modes considered are: $Z_c^+(3900)/Z_c^+(4200) \to \pi^+J/\psi$, $Z_{c1}^+(4050)/Z_{c2}^+(4250) \to \pi^+\chi_{c1}(1P)$ and $Z_c^+(4050)/Z_c^+(4430) \to \pi^+\psi(2S)$. No significant signals are observed in any of the studied modes, and the 90% C.L. upper limits on their product branching fractions in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays and the product of Born cross section and branching fraction for $e^+e^- \to Z_c^+Z_c^{(\prime)-}$ at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV are obtained; $\mathcal{B}(\Upsilon(1S,2S) \to Z_c^+Z_c^{(\prime)-}) \times \mathcal{B}(Z_c^+ \to \pi^+ + c\bar{c})$ ($c\bar{c} = J/\psi$, $\chi_{c1}(1P)$, $\psi(2S)$) within a range of 1 to 50×10^{-6} and $\sigma(e^+e^- \to Z_c^+Z_c^{(\prime)-}) \times \mathcal{B}(Z_c^+ \to \pi^+ + c\bar{c})$ within a range of 0 to 100 fb^{-1}.

4. Summary

We review some results on the study of quarkonia and quarkonium-like states at Belle. The mainly results are summarized below. (1) the enhancement of the transition $\Upsilon(4S) \to \eta\Upsilon(1S)$ with respect to the transition via dipion, (2) the first observation of the process $e^+e^- \to \eta\Upsilon_J(1D)$ and $\Upsilon(4S) \to \eta'\Upsilon(1S)$, and (3) the 90% C.L. upper limits are set for the search for some charmonium-like states, e.g., $X(3872)$, $Y(4660)$ and its spin partner, and Z_c pair.

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