Search for charmonium and charmonium-like states in $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays

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Using samples of 102 million $\Upsilon(1S)$ and 158 million $\Upsilon(2S)$ event samples collected with the Belle detector, we report on the first search for charge-parity-even charmonium and charmonium-like states in $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays. No significant $\chi_{cJ}$ or $\eta_c$ signal is observed and 90% C.L. limits on $\text{BR}(\Upsilon(nS) \rightarrow \gamma \chi_{cJ})$ ($n = 1, 2$ and $J = 1, 2, 3$) are obtained. No significant signal of any charmonium-like state is observed. The product branching fraction limits $\text{BR}(\Upsilon(nS) \rightarrow \gamma X(3872)) \times \text{BR}(X(3872) \rightarrow \pi^+ \pi^- J/\psi)$, $\text{BR}(\Upsilon(nS) \rightarrow \gamma X(3872)) \times \text{BR}(X(3872) \rightarrow \pi^+ \pi^- \pi^0 J/\psi)$, $\text{BR}(\Upsilon(nS) \rightarrow \gamma X(3915)) \times \text{BR}(X(3915) \rightarrow \omega J/\psi)$, and $\text{BR}(\Upsilon(1S) \rightarrow \gamma Y(4140)) \times \text{BR}(Y(4140) \rightarrow \phi J/\psi)$ ($n = 1, 2$) are obtained at the 90% C.L. At the same time, $\text{BR}(\Upsilon(2S) \rightarrow \gamma X(4350)) \times \text{BR}(X(4350) \rightarrow \phi J/\psi)$ is also determined at the 90% C.L. Furthermore, no evidence is found for excited charmonium states below 4.8 GeV/$c^2$.

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1 Introduction

Experimental observations near the charm threshold strongly suggest that the spectrum of resonances with hidden charm is remarkably more rich than suggested by the standard quark-antiquark template and very likely includes states where the heavy-quark $c\bar{c}$ pair is accompanied by light quarks and/or gluons. Lots of new charmonium-like resonances ($XYZ$ particles) in the B factories have been observed in the final states with a charmonium and some light hadrons. They could be candidates for usual charmonium states, however, there are also lots of strange properties shown from these states. These may include exotic states, such as quark-gluon hybrids, meson molecules, and multi-quark states [1]. Many of these new states are established in a single production mechanism or in a single decay mode only. To better understand them, it is necessary to search for such states in more production processes and/or decay modes.

States with $J^{PC} = 1^{--}$ can be studied via initial state radiation (ISR) with the large $\Upsilon(4S)$ data samples at BaBar or Belle, or via $e^+e^-$ collisions directly at the peak energy at, for example, BESIII. For charge-parity-even charmonium states, radiative decays of the narrow $\Upsilon$ states below the open bottom threshold can be examined.

The production rates of the lowest lying $P$-wave spin-triplet ($\chi_{cJ}, J=0, 1, 2$) and $S$-wave spin-singlet ($\eta_c$) states in $\Upsilon(1S)$ radiative decays have been calculated in Ref. [2], where the former is at the part per million level, and the latter is about $5 \times 10^{-5}$. The rates in $\Upsilon(2S)$ decays are estimated to be at the same level [2]. However, there are no such calculations or estimations for “$XYZ$ particles” due to the limited knowledge of their nature.

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Belle ever searched for charmonium and charmonium-like states in $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays [3, 4]. The data used in those analyses include: (1) a 5.7 fb$^{-1}$ data sample collected at the $\Upsilon(1S)$ (102 million $\Upsilon(1S)$ events) and a 1.8 fb$^{-1}$ data sample collected at $\sqrt{s} = 9.43$ GeV (continuum data); (2) a 24.7 fb$^{-1}$ data sample collected at the $\Upsilon(2S)$ peak (158 million $\Upsilon(2S)$ events) and a 1.7 fb$^{-1}$ data sample collected at $\sqrt{s} = 9.993$ GeV (continuum data).

The numbers of the $\Upsilon(1S)$ and $\Upsilon(2S)$ events are determined by counting the hadronic events in the data taken at the $\Upsilon$ peak after subtracting the scaled corresponding continuum background from the data sample collected at the corresponding energy point. The selection criteria for hadronic events are validated with the off-resonance data by comparing the measured $R$ value ($R = \frac{\sigma(e^+e^-\rightarrow h_{hadrons})}{\sigma(e^+e^-\rightarrow \mu^+\mu^-)}$) with CLEO’s result [5].
In this report, we gave the combined results of search for charmonium and charmonium-like states in Υ(1S) and Υ(2S) radiative decays in order to compare easily.

2 Belle and KEKE

The Belle detector operating at the KEKB asymmetry-energy $e^+e^-$ collider [6] is described in detail elsewhere [7]. It is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K^0_L$ mesons and to identify muons (KLM).

3 Search for charmonium(-like) states

We reconstruct $J/\psi$ signals from $e^+e^-$ or $\mu^+\mu^-$ candidates. In order to reduce the effect of bremsstrahlung or final-state radiation, photons detected in the ECL within 0.05 radians of the original $e^+$ or $e^-$ direction are included in the calculation of the $e^+/e^-$ momentum. In order to improve the $J/\psi$ momentum resolution, a mass-constrained fit is performed for $J/\psi$ signals. Different modes have similar $J/\psi$ mass resolutions. The $J/\psi$ signal region is defined as $|M_{\ell^+\ell^-} - m_{J/\psi}| < 30$ MeV/$c^2$ ($\approx 2.5\sigma$), where $m_{J/\psi}$ is the nominal mass of $J/\psi$. The $J/\psi$ mass sidebands are defined as $2.959$ GeV/$c^2 < M_{\ell^+\ell^-} < 3.019$ GeV/$c^2$ and $3.175$ GeV/$c^2 < M_{\ell^+\ell^-} < 3.235$ GeV/$c^2$, and are twice as wide as the signal region.

We search for the $\chi_{cJ}$ in the $\gamma J/\psi$ mode. The energy deposited by the $\chi_{cJ}$ photon is denoted as $\gamma_l$ since its energy is much lower than that of $\gamma_R$ (radiative photon from Υ decay). The $\mu^+\mu^-$ mode shows a clear $J/\psi$ signal, while the $e^+e^-$ mode has some residual radiative Bhabha background. Figure 1 shows the $\gamma_l J/\psi$ invariant mass distribution together with the background estimated from the $J/\psi$ mass sidebands (normalized to the width of the $J/\psi$ signal range) for the combined $e^+e^-$ and $\mu^+\mu^-$ modes after all the selection criteria are applied. In Fig. 1 the left panel is for the Υ(1S) data, where apart from possible weak $\chi_{c0}$ and $\chi_{c1}$ signals, the $J/\psi$ sideband events represent well the signal region, indicating that the production of any of the $\chi_{cJ}$ states is not significant. In Fig. 1 the right panel is for the Υ(2S) data, where no $\chi_{cJ}$ signal is observed. There are no structures at higher masses, where we would expect excited $\chi_{cJ}$ states.

The upper limit on the number ($n^{up}$) of signal events at the 90% C.L. is calculated by solving the equation $\frac{\int_0^{n^{up}} \mathcal{L}(x)dx}{\int_0^\infty \mathcal{L}(x)dx} = 0.9$, where $x$ is the number of signal events, and
\( \mathcal{L}(x) \) is the likelihood function depending on \( x \) from the fit to the data.

Bayesian upper limits on the number of events at the 90% C.L. are found to be 11.5, 13.8, and 2.4 for the \( \chi_{c0} \), \( \chi_{c1} \), and \( \chi_{c2} \) for \( \Upsilon(1S) \) decay, and 2.8, 3.1 and 7.6 for the \( \chi_{c0} \), \( \chi_{c1} \) and \( \chi_{c2} \) for \( \Upsilon(2S) \) decay, respectively.

Figure 1: The \( \gamma J/\psi \) invariant mass distributions in the \( \Upsilon(1S) \) (left panel) and \( \Upsilon(2S) \) (right panel) data samples. There is no clear \( \chi_{cJ} \) signal observed. The solid curve is the best fit, the dashed curve is the background, and the shaded histogram is from the normalized \( J/\psi \) mass sidebands.

To study the \( \gamma \eta_c \) mode, we reconstruct the \( \eta_c \) mass from the invariant masses of \( K_S^0 K^+ \pi^- + \text{c.c.}, \pi^+\pi^- K^+K^- \), \( 2(K^+K^-) \), \( 2(\pi^+\pi^-) \), and \( 3(\pi^+\pi^-) \). Figure 2 shows the combined mass distribution for the five \( \eta_c \) decay modes after all of the selection. The left panel is for \( \Upsilon(1S) \) data, while the right is for \( \Upsilon(2S) \) data. The peak in hadronic mass at the \( J/\psi \) mass, as seen in Fig. 2, can be attributed to the ISR process, \( e^+e^- \rightarrow \gamma_{ISR} J/\psi \), while the accumulation of events within the \( \eta_c \) mass region is small. The shaded histogram in Fig. 2 is the same distribution for the continuum data (not normalized in \( \Upsilon(2S) \) data).

A simultaneous fit is performed to the five final states. The ratios of the \( \eta_c \) \((J/\psi)\) yields in all the channels are fixed to \( \text{BR}_i \epsilon_i \), where each \( \text{BR}_i \) is the \( \eta_c \) \((J/\psi)\) decay branching fraction for the \( i \)-th mode reported by the PDG [8], and \( \epsilon_i \) is the MC-determined efficiency for this mode. The fit function contains a BW function convolved with a Gaussian resolution function (its resolution is fixed to 7.9 MeV/c\(^2\) from MC simulation) describing the \( \eta_c \) signal shape, another Gaussian function describing the \( J/\psi \) signal shape, and a second-order polynomial describing the background shape. The mass and width of the BW function are fixed to the PDG values [8] for the \( \eta_c \). The fitted results are shown in Fig. 2 where the solid line is the sum of the best fit functions in the simultaneous fit, and the dashed line is the sum of the background functions.

The fits yield 46 \( \pm \) 22 and 14 \( \pm \) 20 \( \Upsilon(1S) \rightarrow \gamma \eta_c \) and 14 \( \pm \) 20 \( \Upsilon(2S) \rightarrow \gamma \eta_c \) signal.
events, respectively. The corresponding upper limits on the number of the \( \eta_c \) signal events are estimated to be 72 and 44, respectively, at the 90% C.L.

Figure 2: The mass distributions for a sum of the five \( \eta_c \) decay modes from \( \Upsilon(1S) \) (left panel) and \( \Upsilon(2S) \) (right panel) data, respectively. The solid curve is a sum of the corresponding functions obtained from a simultaneous fit to all the \( \eta_c \) decay modes, and the dashed curve is a sum of the background functions from the fit. The shaded histogram is a sum of the continuum events (not normalized in \( \Upsilon(2S) \) data). The \( J/\psi \) signal is produced via ISR rather than from a radiative decay of an \( \Upsilon \) resonance.

The selection criteria for \( \Upsilon(1S)/\Upsilon(2S) \rightarrow \gamma X(3872), X(3872) \rightarrow \pi^+\pi^- J/\psi \) are similar to those used for ISR \( \pi^+\pi^- J/\psi \) events in \( \Upsilon(4S) \) data [9]. Except for a few residual ISR produced \( \psi(2S) \) signal events, only a small number of events appear above the \( \psi(2S) \) peak in the \( \pi^+\pi^- J/\psi \) invariant mass distribution, as shown in Fig. 3 (left two plots), where the upper plot is for the \( \Upsilon(1S) \) data, while the lower is for the \( \Upsilon(2S) \) data. For \( \Upsilon(1S) \), within the \( X(3872) \) signal region, there is only one event with a mass of 3.870 GeV/c\(^2\). The upper limits at 90% C.L. on the number of the \( X(3872) \) signal events are estimated to be 3.9 and 3.6 from \( \Upsilon(1S) \) and \( \Upsilon(2S) \) decays, respectively.

We validate our analysis by measuring the \( \psi(2S) \) ISR production cross section as observed in the \( \pi^+\pi^- J/\psi \) mode. The measured cross section of \( e^+e^- \rightarrow \gamma_{\text{ISR}} \psi(2S) \) is in agreement with a theoretical calculation of 18.5 pb using PDG [8] values for the \( \psi(2S) \) resonance parameters as input.

We also search for the \( X(3872) \) and \( X(3915) \) in the \( \pi^+\pi^- \pi^0 J/\psi \) mode. We select \( \pi^+ \), \( \pi^- \), and \( J/\psi \) candidates in the \( X(3872) \rightarrow \pi^+\pi^- J/\psi \) mode and a \( \pi^0 \) candidate from a pair of photons with invariant mass within 10 MeV/c\(^2\) of the \( \pi^0 \) nominal mass. Here the \( \pi^0 \) mass resolution is about 4 MeV/c\(^2\) from MC simulation. Figure 3 (right two plots) shows the \( \pi^+\pi^- \pi^0 J/\psi \) invariant mass distributions, where the open histogram is the MC expectation for the \( X(3872) \) signal plotted with an arbitrary normalization. We observe two events in the \( \pi^+\pi^- \pi^0 J/\psi \) mass spectrum between 3.6 GeV/c\(^2\) and 4.8 GeV/c\(^2\) in the \( \Upsilon(1S) \) data. For these two events, the \( \pi^+\pi^- \pi^0 J/\psi \)
masses are 3.67 GeV/c² and 4.23 GeV/c², and the corresponding \( \pi^+\pi^\mp\pi^0 \) masses are 0.54 GeV/c² and 1.04 GeV/c², respectively. The event at 3.67 GeV/c² is likely to be from \( e^+e^- \rightarrow \gamma_{\text{ISR}}J/\psi \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-\pi^0 \ell^+\ell^- \), since 0.9 events are expected from MC simulation. In the \( \Upsilon(2S) \) data, there are a few events scattering in the \( \pi^+\pi^-\pi^0J/\psi \) mass spectrum. No event is observed within the \( X(3872) \) or \( X(3915) \) mass region in the \( \Upsilon(1S) \) data, while there is one event with \( m(\pi^+\pi^-\pi^0J/\psi) \) at 3.923 GeV/c² and \( m(\pi^+\pi^-\pi^0) \) at 0.790 GeV/c² from the \( \Upsilon(2S) \) data. We determine \( n_{\text{up}} \) for the number of \( X(3872) \) signal events to be 2.3 and 4.2 at the 90% C.L. for \( \Upsilon(1S) \) and \( \Upsilon(2S) \) decays, respectively. Assuming that the number of background events is zero, the upper limits \( n_{\text{up}} \) for the number of \( X(3915) \) signal events are 2.3 and 4.4 at the 90% C.L. for \( \Upsilon(1S) \) and \( \Upsilon(2S) \) decays, respectively.

We search for the \( Y(4140) \) and the \( X(4350) \) (only in the \( \Upsilon(2S) \) data) in the \( \phi J/\psi \) mode. The selection criteria are very similar to those in the analysis of \( X(3872) \rightarrow \pi^+\pi^-J/\psi \) and the \( \phi \) is reconstructed from a \( K^+K^- \) pair. According to MC simulation, the \( \phi \) signal region is defined as 1.01 GeV/c² < \( M_{K^+K^-} \) < 1.03 GeV/c². After applying all of the above event selection criteria, there is no clear \( J/\psi \) or \( \phi \) signal in \( \Upsilon(1S) \) or \( \Upsilon(2S) \) data samples. Nor are there candidate events in the \( Y(4140) \) or \( X(4350) \) mass regions. The upper limits on the number of \( Y(4140) \) and \( X(4350) \) signal events are both 2.3 at the 90% C.L.

4 Summary

To summarize, we find no significant signals for the \( \chi_{cJ} \) or \( \eta_c \), as well as for the \( X(3872) \), \( X(3915) \), \( Y(4140) \), or \( X(4350) \) in \( \Upsilon(1S) \) and \( \Upsilon(2S) \) radiative decays. In addition, we find no evidence for excited charmonium states in the invariant mass distributions of all final states below 4.8 GeV/c². Table 1 lists the final results for the upper limits on the branching fractions of all the states studied. In order to calculate conservative upper limits on these branching fractions, the efficiencies have been lowered by a factor of \( 1 - \sigma_{\text{sys}} \), here \( \sigma_{\text{sys}} \) is the total systematic error. The results obtained on the \( \chi_{cJ} \) and \( \eta_c \) production rates are not in contradiction with the calculations in Ref. [2]. No \( X(3872) \), \( X(3915) \), or \( Y(4140) \) signals are observed, and the production rates of the \( \pi^+\pi^-J/\psi \), \( \pi^+\pi^-\pi^0J/\psi \), \( \omega J/\psi \), or \( \phi J/\psi \) modes are found to be less than a few times \( 10^{-6} \) at the 90% C.L.

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Figure 3: (a) Distributions of the $\pi^+\pi^-J/\psi$ invariant mass. (b) Distributions of the $\pi^+\pi^-\pi^0J/\psi$ invariant mass. The upper two plots are for $\Upsilon(1S)$ decay, while the lower for $\Upsilon(2S)$ decay. Points with error bars are data, open histograms are the MC expectation for the $X(3872)$ signal (not normalized). The peak at 3.686 GeV/$c^2$ in (a) is due to $\psi(2S)$ production via ISR.

Table 1: Summary of the limits on $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays to charmonium and charmonium-like states $R$. Here $BR(\Upsilon \to \gamma R)^{up} (B_R)$ is the upper limit at the 90% C.L. on the decay branching fraction in the charmonium state case, and on the product branching fraction in the case of a charmonium-like state.

| State ($R$) | $B_R$ ($\Upsilon(1S)$) | $B_R$ ($\Upsilon(2S)$) |
|------------|--------------------------|--------------------------|
| $\chi_c0$  | $6.5 \times 10^{-4}$     | $1.0 \times 10^{-4}$    |
| $\chi_c1$  | $2.3 \times 10^{-5}$     | $3.6 \times 10^{-6}$    |
| $\chi_c2$  | $7.6 \times 10^{-6}$     | $1.5 \times 10^{-5}$    |
| $\eta_c$   | $5.7 \times 10^{-5}$     | $2.7 \times 10^{-5}$    |
| $X(3872) \to \pi^+\pi^-J/\psi$ | $1.6 \times 10^{-6}$ | $0.8 \times 10^{-6}$ |
| $X(3872) \to \pi^+\pi^-\pi^0J/\psi$ | $2.8 \times 10^{-6}$ | $2.4 \times 10^{-6}$ |
| $X(3915) \to \omega J/\psi$ | $3.0 \times 10^{-6}$ | $2.8 \times 10^{-6}$ |
| $Y(4140) \to \phi J/\psi$ | $2.2 \times 10^{-6}$ | $1.2 \times 10^{-6}$ |
| $X(4350) \to \phi J/\psi$ | $\cdots$ | $1.3 \times 10^{-6}$ |
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