Bottomonium results at Belle

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Originally designed for CP violation studies in the B meson system, the B-Factories recently showed an exciting capability for improving our experimental knowledge in the field of hadron spectroscopy. We review results on bottomonium spectroscopy from the Belle experiment at the KEK-B e+e- collider and present exciting new results from the unique large data set taken at the Υ(5S) resonance.

1 Introduction

The Belle Collaboration has collected a large sample of e^+e^- collisions at the energy of the $\Upsilon(5S)$ resonance, which lies above the threshold for production of B_s meson pairs, primarily for the purpose of studying decays of B_s. There have been a number of unexpected results on the non-$B_s\overline{B}_s$ decays of the $\Upsilon(5S)$. In particular, anomalously large rates for dipion transitions to lower bottomonium states $\Upsilon(5S) \to (\Upsilon(1S), \Upsilon(2S), \Upsilon(3S))\pi^+\pi^-$ have been observed [1]. If these signals are attributed entirely to the $\Upsilon(5S)$ decays, the measured partial decay widths $\Gamma[\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-] \sim 0.5\,\text{MeV}$ are about two orders of magnitude larger than typical widths for dipion transitions among $\Upsilon(nS)$ states with $n \leqslant 4$.
Recently the CLEO-c Collaboration observed the process $e^+e^- \to h_c(1P)\pi^+\pi^-$ at a rate comparable to the process $e^+e^- \to J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4170\,\text{MeV}$ and found an indication of an even higher transition rate at the $Y(4260)$ energy [2]. This implies that the $h_b(mP)$ production might be enhanced in the region of the Y_b and motivates a search for the $h_b(mP)$ in the $\Upsilon(5S)$ data.
We use the full $\Upsilon(5S)$ data sample with the integrated luminosity of $121.4\,\text{fb}^{-1}$ collected near the peak of the $\Upsilon(5S)$ resonance with the Belle detector [4] at the KEKB asymmetric-energy e^+e^- collider [3].

2 $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ and $\Upsilon(nS)\pi^+\pi^-$ data analysis

We observe the $h_b(1P)$ and $h_b(2P)$ in the missing mass spectrum of $\pi^+\pi^-$ pairs. The $\pi^+\pi^-$ missing mass is defined as $MM(\pi^+\pi^-) \equiv \sqrt{(E_{c.m.} - E^*_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}}$, where $E_{c.m.}$ is the

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center-of-mass (c.m.) energy, $E^*_{\pi^+\pi^-}$ and $p^*_{\pi^+\pi^-}$ are the $\pi^+\pi^-$ energy and momentum measured in the c.m. frame. The details of the analysis can be founnd in [5]. The $MM(\pi^+\pi^-)$ distribution for the selected $\pi^+\pi^-$ pairs is shown in Fig. 1(a). In this figure only the $\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ transitions are discernible.
To fit the $MM(\pi^+\pi^-)$ spectrum we separate it into three adjacent regions with boundaries at $MM(\pi^+\pi^-) = 9.3\,\mathrm{GeV}/c^2$, $9.8\,\mathrm{GeV}/c^2$, $10.1\,\mathrm{GeV}/c^2$ and $10.45\,\mathrm{GeV}/c^2$. We fit every region separately to better control the complicated shape of the combinatorial background, which is described by a Chebyshev polynomial of 6-7th order. In region 3 we subtract the K^0_S contribution bin-by-bin, while in other regions its shape is smooth and is absorbed into combinatorial background. The signal peaks are described by Gaussians with paramenters obtained from exclusive decays of the $\Upsilon(nS)$ to $\mu^+\mu^-$. The $MM(\pi^+\pi^-)$ spectrum with the combinatorial background and K^0_S contributions subtracted, and the signal function resulting from the fit overlaid, is shown in Fig. 1(b). The significance of the $h_b(1P)$ and

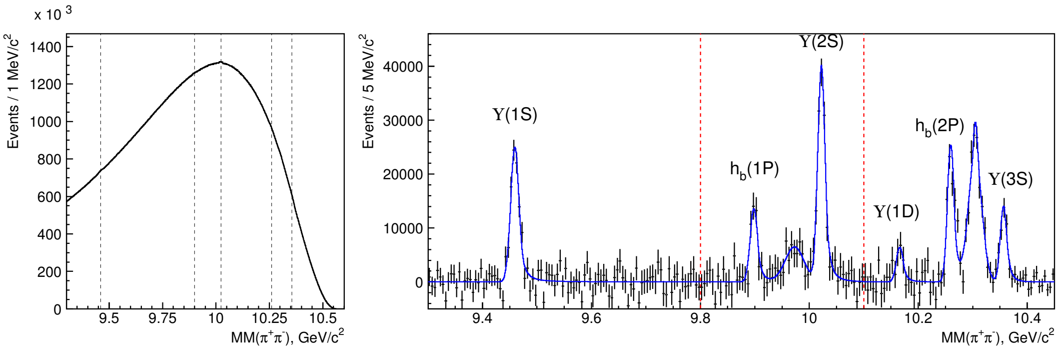

Figure 1: (a)The $MM(\pi^+\pi^-)$ distribution for the selected $\pi^+\pi^-$ pairs. Vertical lines indicate the locations of the $\Upsilon(1S)$, $h_b(1P)$, $\Upsilon(2S)$, $h_b(2P)$ and $\Upsilon(3S)$ signals. (b) The $MM(\pi^+\pi^-)$ spectrum with the combinatorial background contributions subtracted (dots with error bars) and signal component of the fit function (solid histogram).

$h_b(2P)$ signals which includes the systematic uncertainty is 5.5σ and 11.2σ, respectively. This is the first observation of the $h_b(1P)$ and $h_b(2P)$ spin-singlet bottomonium states in the reaction $e^+e^- \to h_b(mP)\pi^+\pi^-$ at the $\Upsilon(5S)$ energy. We measure the masses and the cross sections relative to the $e^+e^- \to \Upsilon(2S)\pi^+\pi^-$ cross-section: $M = 9898.25 \pm 1.06^{+1.03}_{-1.07}\,\mathrm{MeV}/c^2$, $R = 0.407 \pm 0.079^{+0.043}_{-0.076}$ for the $h_b(1P)$ and $M = 10259.76 \pm 0.64^{+1.43}_{-1.03}\,\mathrm{MeV}/c^2$, $R = 0.78 \pm 0.09^{+0.22}_{-0.10}$ for the $h_b(2P)$. The masses do not differ significantly from the center-of-gravity of the corresponding χ_{bJ} states. For the hyperfine splitting we find $\Delta M_{\mathrm{HF}} = 1.62 \pm 1.52\,\mathrm{MeV}/c^2$ for the $h_b(1P)$ and $0.48^{+1.57}_{-1.22}\,\mathrm{MeV}/c^2$ for the $h_b(2P)$. The values of R are comparable with unity indicate that the $h_b(1P)$ and $h_b(2P)$ are produced via an exotic process that violates the suppression of heavy quark spin-flip.
For further study we investigate resonant structure of these decays [7]. Because of high background Dalitz plot analysis is impossible with current statistics, therefore we study the one-dimensional distributions in $M(h_b(mP)\pi)$. We define the $M(h_b(mP)\pi^+)$ as a missing

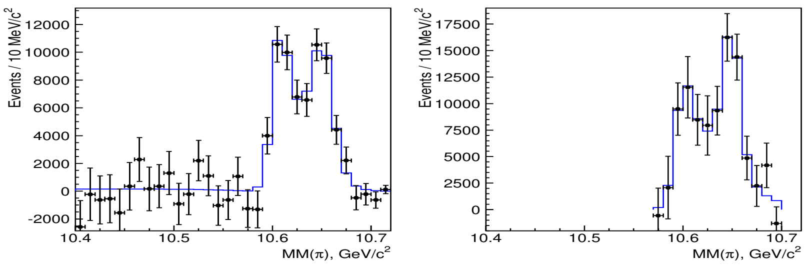

Figure 2: The yield of the $h_b(1P)$ (a) and $h_b(2P)$ (b) as a function of $MM(\pi)$ (points with error bars) and results of the fit (histogram).

mass of the opposite sign pion, $MM(\pi^-)$. We measure the yield of signal decays as a function of the $MM(\pi^\pm)$ by fitting the $MM(\pi^+\pi^-)$ spectra in the bins of $MM(\pi^\pm)$. We combine the $MM(\pi^+\pi^-)$ spectra for the corresponding $MM(\pi^+)$ and $MM(\pi^-)$ bins and we use half of the phase-space to avoid double counting. Results of fits for the $h_b(1P)$ yield as a function of $MM(\pi)$ are shown in Fig. 2. The $h_b(1P)$ yield exhibits a clear two-peak structure without any significant non-resonant contribution.

We perform a χ^2 fit to the $MM(\pi)$ distributions. We assume that spin-parity for both $Z_b(10610)$ and $Z_b(10650)$ is $J^P = 1^+$, therefore in the fit function we use a coherent sum of two P-wave Breit-Wigner amplitudes and a non-resonant contribution:$f = A\,|BW(s, M_1, \Gamma_1) + ae^{i\phi}BW(s, M_2, \Gamma_2) + be^{i\psi}|^2\ \frac{qp}{\sqrt{s}}$, where $\sqrt{s} \equiv MM(\pi)$; the variables A, M_k, Γ_k ($k = 1, 2$), a, ϕ, b and ψ are floating in the fit. The non-resonant amplitude is found to be consistent with zero. The results of the fit are shown in Fig. 2 and are summarized in Table 2. We find that the hypothesis of two resonances is favored over the hypothesis of a single resonance (no resonances) at the 7.4 σ (17.9 σ) level. The parameters of the $Z_b(10610)$ and $Z_b(10650)$ obtained in the fit of $h_b(1P)$ and $h_b(2P)$ are consistent with each other.

To select $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ candidate events, we require the presence of a pair of muon candidates with an invariant mass in the range of 8.0 GeV/c^2 $< M(\mu^+\mu^-) <$ 11.0 GeV/c^2 and two pion candidates of opposite charge. Candidate $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ events are identified by the invariant mass of the $\mu^+\mu^-$ combination and the missing mass associated with the $\pi^+\pi^-$ system calculated as $MM(\pi^+\pi^-) = \sqrt{(E_{c.m.} - E^*_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}}$, where $E_{\rm c.m.}$ is the c.m. energy and $E^*_{\pi^+\pi^-}$ and $p^*_{\pi^+\pi^-}$ are the energy and momentum of the $\pi^+\pi^-$ system measured in the c.m. frame.

The amplitude analyses of the three-body $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ decays that are reported here are performed by means of unbinned maximum likelihood fits to two-dimensional Dalitz distributions. The logarithmic likelihood function $\mathcal{L}$ is then constructed as

$$\mathcal{L} = -2\sum \log(f_{\rm sig}S(s_1, s_2) + (1 - f_{\rm sig})B(s_1, s_2)), \tag{1}$$

where $S(s_1, s_2) = |M(s_1, s_2)|^2$ folded with the detector resolution function, $B(s_1, s_2) = 1$ and $f_{\rm sig}$ is a fraction of signal events in the data sample. Both $S(s_1, s_2)$ and $B(s_1, s_2)$ are corrected

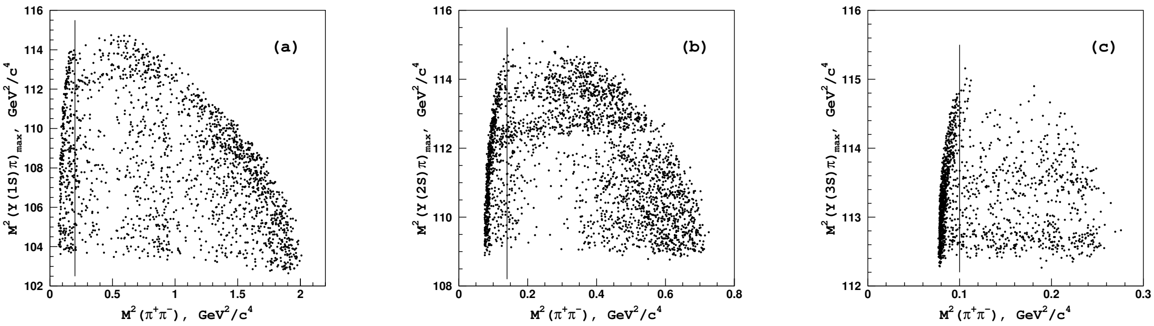

Figure 3: Dalitz plots for $\Upsilon(nS)\pi^+\pi^-$ events in the (a) $\Upsilon(1S)$; (b) $\Upsilon(2S)$; (c) $\Upsilon(3S)$ signal regions. The regions to the right of the vertical lines are included in the fit procedure.

for the reconstruction efficiency.
The background distribution functions were obtained from the $\Upsilon(nS)$ mass sidebands. There is a strong concentration of background events in the very low $\pi^+\pi^-$ invariant mass region; these are due to photon conversion on the innermost parts of the Belle detector. We exclude this region by applying the requirements on the $\pi^+\pi^-$ invariant mass. The background distribution for the remaining region is consistent with the uniform one.
The variation of reconstruction efficiency across the Dalitz plot is determined from MC simulation. The fraction of signal events in the signal region for each of the three $\Upsilon(nS)\pi^+\pi^-$ final states is determined from a fit to the corresponding $MM(\pi^+\pi^-)$ spectrum using a Crystal Ball function [6] for the Υ signal and a linear function for the combinatorial background component.
Figure 3 shows Dalitz plots of the events in the signal regions for the three decay channels under study. In all cases, two horizontal bands are evident in the $\Upsilon(nS)\pi$ system near 10.61 GeV/c^2 ($\sim$ 112.6 GeV^2/c^4) and 10.65 GeV/c^2 ($\sim$ 113.3 GeV^2/c^4). In the following we refer to these structures as $Z_b(10610)$ and $Z_b(10650)$, respectively.

We use the following parameterization for the $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ three-body decay amplitude: $M(s_1, s_2) =$
$BW(s_1, M_2, \Gamma_2) + BW(s_2, M_2, \Gamma_2) + ae^{i\delta}(BW(s_1, M_2, \Gamma_2) + BW(s_2, M_2, \Gamma_2)) + A_{f_0} + A_{f_2} + A_{NR}$, where $s_{1\ 2} = M^2(\Upsilon(nS)\pi^\pm)$. Here we assume that the dominant contributions come from the amplitudes that conserve the orientation of the spin of the heavy quarkonium state and, thus, both pions in the cascade decay $\Upsilon(5S) \to Z_b\pi \to \Upsilon(nS)\pi^+\pi^-$ are emitted in an S-wave with respect to the heavy quarkonium system. Consequently, we parameterize the observed $Z_b(10610)$ and $Z_b(10650)$ peaks with an S-wave Breit-Wigner function without $s-$dependence of the resonance width Γ. We also include amplitudes A_{f_0} and A_{f_2} to account for possible contributions in the $\pi^+\pi^-$ channel from $f_0(980)$ scalar and $f_2(1270)$ tensor states, respectively and non-resonant amplitude [8] $A_{\rm NR} = a_1^{\rm nr} \cdot e^{i\delta_1^{\rm nr}} + a_2^{\rm nr} \cdot e^{i\delta_2^{\rm nr}} \cdot s_3$, where $s_3 = M^2(\pi^+\pi^-)$ and $a_1^{\rm nr}$, $a_2^{\rm nr}$, $\delta_1^{\rm nr}$ and $\delta_2^{\rm nr}$ are free parameters of the fit.
Results of the fits are summarized in Table 2. The combined statistical significance of the two peaks exceeds 10 sigma for all tested models and for all $\Upsilon(nS)\pi^+\pi^-$ channels.

Table 1: The probabilities at which different J^P hypotheses are disfavored compared to the 1^+ hypothesis.

<table>
<tr><td rowspan="2">J^P</td><td colspan="3">$Z_b(10610)$</td><td colspan="3">$Z_b(10650)$</td></tr>
<tr><td>$\Upsilon(2S)\pi^+\pi^-$</td><td>$\Upsilon(3S)\pi^+\pi^-$</td><td>$h_b(1P)\pi^+\pi^-$</td><td>$\Upsilon(2S)\pi^+\pi^-$</td><td>$\Upsilon(3S)\pi^+\pi^-$</td><td>$h_b(1P)\pi^+\pi^-$</td></tr>
<tr><td>1^-</td><td>$3.6\,\sigma$</td><td>$0.3\,\sigma$</td><td>$0.3\,\sigma$</td><td>$3.7\,\sigma$</td><td>$2.6\,\sigma$</td><td>$2.7\,\sigma$</td></tr>
<tr><td>2^+</td><td>$4.3\,\sigma$</td><td>$3.5\,\sigma$</td><td rowspan="2">$4.3\,\sigma$</td><td>$4.4\,\sigma$</td><td>$2.7\,\sigma$</td><td rowspan="2">$2.1\,\sigma$</td></tr>
<tr><td>2^-</td><td>$2.7\,\sigma$</td><td>$2.8\,\sigma$</td><td>$2.9\,\sigma$</td><td>$2.6\,\sigma$</td></tr>
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We perform angular analyses to check consistency of the $J^P = 1^+$ assignment for the $Z_b(10610)$ and $Z_b(10650)$ states and to attempt to discriminate against other J^P hypotheses; we consider $J^P = 1^-, 2^+$ and 2^-. The 0^+ (0^-) assignment is forbidden by parity conservation in $Z_b \to \Upsilon(nS)\pi$ ($Z_b \to h_b(mP)\pi$) decays. We use the polar angles of the pions (denoted as θ_1 for a pion from the $Y(5S)$ decay and θ_2 for a pion from the Z_b decay), the spatial angle, $\theta_{\pi\pi}$, between the two pions and the angle, ϕ_p, between the plane defined by the pion from $Y(5S)$ decay and the beam direction and the plane defined by the two pions. Since the Z_b velocity is very small, $\beta < 0.02$, we neglect its recoil motion and measure all pion momenta in the c.m. frame. We assume that only the lowest wave contributes to the decay in the cases where more than one wave is possible.

We perform a binned maximum likelihood fit to these distributions. The fit function is a sum of the Z_b signal, non-resonant component and combinatorial background described by a properly normalized $MM(\pi^+\pi^-)$ sidebands. The non-resonant contribution varies with the $\cos\theta_{\pi\pi}$, therefore this variable is not used. The fit function is corrected for efficiency. The only floating parameter in the fit is the normalization of the Z_b signal component.The probabilities at which the 1^-, 2^+ and 2^- hypotheses are disfavored compared to the 1^+ hypothesis are calculated as $\sqrt{\Delta 2 \log L}$ and given in Table 1. The presented numbers indicate that the 1^+ hypothesis for both $Z_b(10610)$ and $Z_b(10650)$ provides the best description of angular distributions among all other hypotheses with $J \leqslant 2$.

Table 2: Z_b and Z_b' parameters obtained from $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ analyses. Quoted values are in MeV$/c^2$ for masses, in MeV for widths and in degrees for the relative phase. Relative amplitude is defined as $a_{Z_b}/a_{Z_b'}$.

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M(Z_b(10610))$	$10609 \pm 3 \pm 2$	$10616 \pm 2^{+3}_{-4}$	$10608 \pm 2^{+5}_{-2}$	$10605.1 \pm 2.2\,^{+3.0}_{-1.0}$	$10596 \pm 7\,^{+5}_{-2}$
$\Gamma(Z_b(10610))$	$22.9 \pm 7.3 \pm 2$	$21.1 \pm 4^{+2}_{-3}$	$12.2 \pm 1.7 \pm 4$	$11.4\,^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$	$16\,^{+16}_{-10}\,^{+13}_{-4}$
$M(Z_b(10650))$	$10660 \pm 6 \pm 2$	$10653 \pm 2 \pm 2$	$10652 \pm 2 \pm 2$	$10654.5 \pm 2.5\,^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$
$\Gamma(Z_b(10650))$	$12 \pm 10 \pm 3$	$16.4 \pm 3.6^{+4}_{-6}$	$10.9 \pm 2.6^{+4}_{-2}$	$20.9\,^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$	$12\,^{+11}_{-9}\,^{+8}_{-2}$
Rel. amplitude	$0.59 \pm 0.19^{+0.09}_{-0.03}$	$0.91 \pm 0.11^{+0.04}_{-0.03}$	$0.73 \pm 0.10^{+0.15}_{-0.05}$	$1.8\,^{+1.0}_{-0.7}\,^{+0.1}_{-0.5}$	$1.3\,^{+3.1}_{-1.1}\,^{+0.4}_{-0.7}$
Rel. phase,	$53 \pm 61^{+5}_{-50}$	$-20 \pm 18^{+14}_{-9}$	$6 \pm 24^{+23}_{-59}$	$188\,^{+44}_{-58}\,^{+4}_{-9}$	$255\,^{+56}_{-72}\,^{+12}_{-183}$

3 Discussion and Conclusions

In conclusion, we have observed two charged bottomonium-like resonances, the $Z_b(10610)$ and $Z_b(10650)$, with signals in five different decay channels, $\Upsilon(nS)\pi^{\pm}$ ($n = 1, 2, 3$) and $h_b(mP)\pi^{\pm}$ ($m = 1, 2$). Parameters of the resonances as measured in different channels are summarized in Table 2. All channels yield consistent results. A simple weighted averages over all five channels give $M[Z_b(10610)] = 10608.4 \pm 2.0\,\mathrm{MeV}/c^2$, $\Gamma[Z_b(10610)] = 15.6 \pm 2.5\,\mathrm{MeV}$ and $M[Z_b(10650)] = 10653.2 \pm 1.5\,\mathrm{MeV}/c^2$, $\Gamma[Z_b(10650)] = 14.4 \pm 3.2\,\mathrm{MeV}$, where statistical and systematic errors are added in quadrature.
The measured masses of these states exceed by only a few MeV/c^2 the thresholds for the open beauty channels $B^*\overline{B}$ (10604.6 MeV) and $B^*\overline{B}^*$ (10650.2 MeV). This "coincidence" can be explained by a molecular-like type of new states, *i.e.*, their structure is determined by the strong interaction dynamics of the $B^*\overline{B}$ and $B^*\overline{B}^*$ meson pairs.
The widths of both states are similar and are of the order of $15\,\mathrm{MeV}/c^2$. The $Z_b(10610)$ production rate is similar to the $Z_b(10650)$ production rate for every decay channel. Their relative phase is consistent with zero for the final states with the $\Upsilon(nS)$ and consistent with 180 degree for the final states with the $h_b(mP)$.
The $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ decays seem to be saturated by the $Z_b(10610)$ and $Z_b(10650)$ intermediate states; this decay mechanism is responsible for the high rate of the $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ process measured recently by the Belle Collaboration.
Analysis of angular distributions for charged pions favors the $J^P = 1^+$ spin-parity assignment for both $Z_b(10610)$ and $Z_b(10650)$. Since the $\Upsilon(5S)$ has negative G-parity, Z_b states will have opposite G-parity due to emission of the pion.

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