PROCEEDINGS OF SCIENCE

Study on $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ and $\Upsilon(5S) \to \Upsilon(1S, 2S)\eta^{(\prime)}$

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We report the first measurement of exclusive cross sections for $e^+e^- \to B\bar{B}$, $e^+e^- \to B\bar{B}^*$, and $e^+e^- \to B^*\bar{B}^*$ in the energy range from 10.63 GeV to 11.02 GeV. The B mesons are fully reconstructed in a large number of hadronic final states, and the three channels are distinguished using the beam-energy-constrained mass variable. For each channel, the cross section shows an oscillatory behavior, with multiple maxima and minima. The final results on $\Upsilon(5S) \to \Upsilon(1S, 2S)\eta$ and $\Upsilon(5S) \to \Upsilon(1S)\eta'$ branching fractions are also presented. All these results are based on data collected by the Belle experiment at the KEKB asymmetric-energy e^+e^- collider.

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1. Introduction

Different anomalies have been recently observed in transitions from bottomonium states above the $B\bar{B}$ threshold – $\Upsilon(4S)$, $\Upsilon(10860)$, and $\Upsilon(11020)$. There are unexpectedly high rates of dipion and η transitions to lower bottomonium like $\Upsilon(1S,2S)$ and $h_b(1P,2P)$ [1]. Naive quark-antiquark models like QCDME fail to predicts such a behavior, while possible interpretations imply higher states to be exotic tetra-quark states or meson molecules.

Thus, it is of special interest to study similar processes like $\Upsilon(5S) \to \Upsilon(1S,2S)\eta^{(\prime)}$, and to study cross section of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$, which provide information about the structure of the $\Upsilon(4S)$, $\Upsilon(10860)$, and $\Upsilon(11020)$ resonances.

2. Study on $e^+e^- \to B^{(*)}\bar{B}^{(*)}$

Here we report the first measurement of the energy dependence of the $e^+e^- \to B\bar{B}$, $e^+e^- \to B\bar{B}^*$, and $e^+e^- \to B^*\bar{B}^*$ exclusive cross sections. The analysis is based on data samples of 571 fb^{-1} on the $\Upsilon(4S)$ resonance, 121 fb^{-1} on the $\Upsilon(5S)$ resonance, and about 20 fb^{-1} of the energy scan in range from 10.63 GeV to 11.02 GeV. These data samples were collected by the Belle detector [2] at the KEKB asymmetric energy e^+e^- collider.

Our approach is to perform a full reconstruction of one B meson in hadronic channels, and then to identify the $B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$ signals using M_{bc} distribution, $M_{bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$, where $E_{\rm cm}$ is the center-of-mass (c.m.) energy and p_B is the B-candidate momentum measured in the c.m. frame. The M_{bc} distribution for $B\bar{B}$ events peaks at the nominal B-meson mass, m_B, while the distributions for $B\bar{B}^*$ and $B^*\bar{B}^*$ events peak approximately at $m_B - \frac{\Delta m_{B^*}}{2}$ and $m_B - \Delta m_{B^*}$, respectively, where Δm_{B^*} is the mass difference of the B^* and B mesons. To reconstruct B mesons in a large number of hadronic final states we apply the Full Event Interpretation (FEI) package [3] based on Fast Boosted Decision Tree algorithm. The energy of the B candidate, E_B, is not included into the FEI training and is used in the M_{bc} *versus* ΔE plane to study background, where $\Delta E = E_B - E_{\rm cm}/2$. We find that there is a peaking background in the M_{bc} distribution which is primarily due to misreconstructed soft photons. Signal regions on ΔE are optimized using overall figure of merit (FoM) defined as $N_{\rm S}/\sqrt{N_{\rm S} + N_{\rm B}}$, where where $N_{\rm S}$ and $N_{\rm B}$ are the numbers of signal and background events, respectively.

We construct the M_{bc} fit function in which the signal shape is calculated based on the $E_{\rm cm}$ spread, the cross section energy dependence, and the momentum resolution. The cross section is described by a high-order Chebyshev polynomial. Thus, we perform simultaneous fit to the M_{bc} distribution and to the cross section energy dependence so that the dressed cross sections are calculated as

$$\sigma^{\rm dressed} = \frac{N}{(1+\delta_{\rm ISR})L\varepsilon},$$

where $N/(1+\delta_{\rm ISR})$ is obtained directly from the fit as describe in previous scan paper [4], L is the integrated luminosity and ε is an efficiency. The efficiency at the $\Upsilon(4S)$ energy is determined as

$$\varepsilon_{\Upsilon(4S)} = \frac{N_B(\Upsilon(4S))}{2N_{B\bar{B}}(\Upsilon(4S))} = (0.4690 \pm 0.0077) \times 10^{-3},$$

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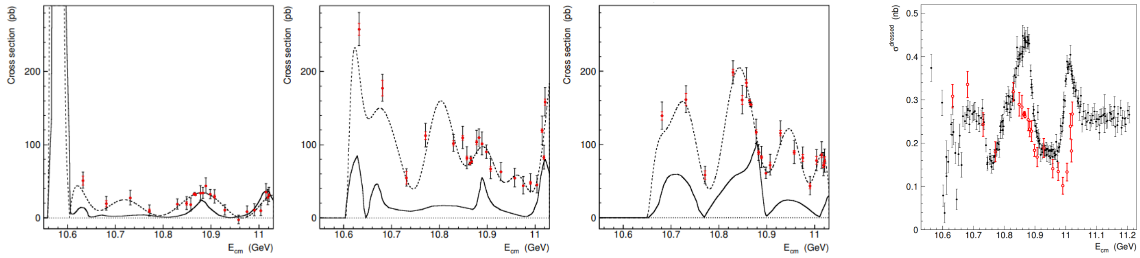

Figure 1: Fitted dressed cross sections (dashed) in comparison with predictions of the Unitarized Quark Model (solid) for $B\bar{B}$ (a), $B\bar{B}^*$ (b), and $B^*\bar{B}^*$ (c), and (d) the sum of measured $B^{(*)}\bar{B}^{(*)}$ cross sections (red dots) in comparison with the total $b\bar{b}$ dressed cross section (black dots).

where $N_B(\Upsilon(4S))$ is the measured B meson signal yield and $N_{B\bar{B}}(\Upsilon(4S)) = (619.6\pm9.4)\times10^6$ [2]. The efficiency at the $\Upsilon(5S)$ energy is determined by comparing the B meson yields at the $\Upsilon(4S)$ energy and at the $\Upsilon(5S)$ energy for five well known final states with low multiplicity reconstructed without application of FEI. The ratio of the efficiencies at $\Upsilon(5S)$ and $\Upsilon(4S)$, 1.049 ± 0.017, agrees with the MC expectation of 1.028 ± 0.004. Moreover, the MC shows that the dependence of the efficiency on the B meson momentum is consistent with being linear. Thus, for all energies and various $B^{(*)}\bar{B}^{(*)}$ final states we determine the efficiency ε based on the average momentum and the values $\varepsilon_{\Upsilon(4S)}$ and $\varepsilon_{\Upsilon(5S)}$, assuming linear dependence on the B meson momentum.

The results for all final states are shown on Figure 1 and their sum is shown on Figure 1. The main contributions to the systematic uncertainties are efficiency, luminosity, shape of peaking background, and cross section shape's parameterization and statistical uncertainty, with total uncertainty ranging from 3.80% to 4.09% at $\Upsilon(5S)$.

3. Study on $\Upsilon(5S) \to \Upsilon(1S,2S)\eta^{(\prime)}$

Here we report the study of hadronic transitions between bottomonium states with emission of an $\eta^{(\prime)}$ meson at $\sqrt{s} = 10.866$ GeV. The process $e^+e^- \to \Upsilon(2S)\eta$ is studied in two different modes: the first decay chain $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(1S) \to \mu^+\mu^-$, $\eta \to \gamma\gamma$ denoted as $\Upsilon(2S)\eta[\gamma\gamma]$; the second decay chain $\Upsilon(2S) \to \mu^+\mu^-$, $\eta \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$ denoted as $\Upsilon(2S)\eta[3\pi]$. The process $e^+e^- \to \Upsilon(1S)\eta$ is studied in the decay chain $\Upsilon(1S) \to \mu^+\mu^-$, $\eta \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$ denoted as $\Upsilon(1S)\eta[3\pi]$. The process $e^+e^- \to \Upsilon(1S)\eta'$ is studied in two different modes: the first decay chain $\Upsilon(1S) \to \mu^+\mu^-$, $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$ denoted as $\Upsilon(1S)\eta'[\pi\pi\eta]$; the second decay chain $\Upsilon(1S) \to \mu^+\mu^-$, $\eta' \to \rho^0\gamma$, $\rho^0 \to \pi^+\pi^-$ denoted as $\Upsilon(1S)\eta'[\rho\gamma]$ and is the only process with the $\mu^+\mu^-\pi^+\pi^-\gamma$ final state, while other processes lead to the $\mu^+\mu^-\pi^+\pi^-\gamma\gamma$ final state. The analysis is based on the data sample of 121 fb^{-1} on the $\Upsilon(5S)$ resonance collected by the Belle detector [2] at the KEKB asymmetric energy e^+e^- collider.

We fully reconstruct all modes and select events using kinematic variables. The following set of selection variables are common to all processes: the angle Ψ between the total momentum of the photons and the total momentum of the charged particles in the CM frame, the invariant mass of the muon pair $M_{\mu\mu}$ (corresponding to the $\Upsilon(1S,2S)$), and the total reconstructed energy of the final-state particles, $E_{\rm tot} = E_{\pi\pi\gamma(\gamma)} + \sqrt{M^2_{\Upsilon(1S,2S)} + \vec{P}^2_{\mu\mu}}$. These variables are used to select

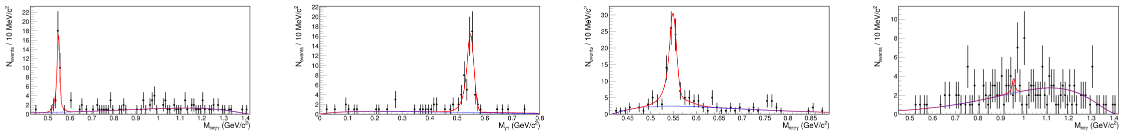

Figure 2: The experimental signal $M_{\eta^{(\prime)}}$ distribution for $\Upsilon(2\mathrm{S})\eta[\gamma\gamma]$ (a), $\Upsilon(2\mathrm{S})\eta[3\pi]$ (b), $\Upsilon(1\mathrm{S})\eta[3\pi]$ (c), and $\Upsilon(1\mathrm{S})\eta'[\rho\gamma]$ (d) fitted to the sum of the MC signal function and background function $(x-p_1)^{p_2}e^{p_3 x}$.

exclusive decay chains that result in the same final states $\mu^+\mu^-\pi^+\pi^-\gamma(\gamma)$. Other mode-specific selection requirements are listed below. A neutral pion in the $\Upsilon(1\mathrm{S},2\mathrm{S})\eta[3\pi]$ modes and η meson in the $\Upsilon(1\mathrm{S})\eta'[\pi\pi\eta]$ mode are reconstructed from the $\pi^0(\eta) \to \gamma\gamma$ decays with the invariant mass $M_{\gamma\gamma}$. A ρ^0 resonance in the $\Upsilon(1\mathrm{S})\eta'[\rho\gamma]$ mode is reconstructed from the $\rho^0 \to \pi^+\pi^-$ decay with $M_{\pi\pi}$. For the $\Upsilon(2\mathrm{S})\eta[\gamma\gamma]$ final state the $\Upsilon(2\mathrm{S})$ meson is reconstructed via its decay chain $\Upsilon(2\mathrm{S}) \to \Upsilon(1\mathrm{S})\pi^+\pi^-$ with $M_{\mu\mu\pi\pi} - M_{\mu\mu}$. In case of multiple decay candidates, the $\mu\mu\pi\pi\gamma(\gamma)$ combination with Ψ closest to π radian is chosen as the best candidate.

The signal distribution for all modes is the $M_{\eta^{(\prime)}}$ ($M_{\gamma\gamma}$, $M_{\pi\pi\gamma\gamma}$ or $M_{\pi\pi\gamma}$) invariant mass fitted by a sum of the Crystal Ball function [5] and a Gaussian. The branching fraction calculated as

$$\mathcal{B}(\Upsilon(5\mathrm{S}) \to \mathrm{X}) = \frac{\mathrm{N_{sig}}}{\mathrm{L}\mathcal{B}\varepsilon}\frac{1}{\sigma_{\mathrm{b\bar{b}}}},$$

where N_{sig} is the signal yield, L is the integrated luminosity, $\mathcal{B}$ is the product of the intermediate branching fractions for the process, and ε is the reconstruction efficiency determined from the Monte-Carlo simulation.

The experimental distributions are shown on Figure 2 and the results are shown in Table 1. The main contributions to the systematic uncertainties are particle reconstruction, luminosity uncertainty, selection criteria, and intermediate branching fractions, with total uncertainty ranging from 8.9% to 9.5%. For the $\Upsilon(2\mathrm{S})\eta[\gamma\gamma]$, $\Upsilon(2\mathrm{S})\eta[3\pi]$, and $\Upsilon(1\mathrm{S})\eta[3\pi]$ modes statistical significance exceeds 10σ, thus we claim the first observation of these processes. For the $\Upsilon(1\mathrm{S})\eta'[\pi\pi\eta]$ and the $\Upsilon(1\mathrm{S})\eta'[\rho\gamma]$ modes the signal yield is consistent with zero and only upper limits are set using a pseudo-experiment method. We also calculate $\frac{\Gamma(\Upsilon(5\mathrm{S})\to\Upsilon(1\mathrm{S})\eta)}{\Gamma(\Upsilon(5\mathrm{S})\to\Upsilon(1\mathrm{S})\pi^+\pi^-)} = 0.19 \pm 0.04 \pm 0.01$, $\frac{\Gamma(\Upsilon(5\mathrm{S})\to\Upsilon(2\mathrm{S})\eta)}{\Gamma(\Upsilon(5\mathrm{S})\to\Upsilon(2\mathrm{S})\pi^+\pi^-)} = 0.51 \pm 0.06 \pm 0.04$, and $\frac{\Gamma(\Upsilon(5\mathrm{S})\to\Upsilon(1\mathrm{S})\eta')}{\Gamma(\Upsilon(5\mathrm{S})\to\Upsilon(1\mathrm{S})\eta)} < 0.09$ ($CL = 90\%$).

Table 1: Signal yield N_{sig} for all modes and averaged over modes branching fraction $\mathcal{B}$.

Process	Mode	N_{sig}	$\mathcal{B}$
$\Upsilon(5S) \to \Upsilon(1S)\eta$	$\Upsilon(1\mathrm{S})\eta[3\pi]$	32.6 ± 5.9	$(0.85 \pm 0.15 \pm 0.08) \times 10^{-3}$
$\Upsilon(5S) \to \Upsilon(2S)\eta$	$\Upsilon(2\mathrm{S})\eta[\gamma\gamma]$	59.5 ± 8.3	$(4.13 \pm 0.41 \pm 0.37) \times 10^{-3}$
	$\Upsilon(2\mathrm{S})\eta[3\pi]$	73.8 ± 10.7	
$\Upsilon(5S) \to \Upsilon(1S)\eta'$	$\Upsilon(1\mathrm{S})\eta'[\pi\pi\eta]$	< 5.2, $CL = 90\%$	$< 6.9 \times 10^{-5}$, $CL = 90\%$
	$\Upsilon(1\mathrm{S})\eta'[\rho\gamma]$	< 5.6, $CL = 90\%$	

4. Conclusion

We report the first measurement of exclusive cross sections for $e^+e^- \to B\bar{B}$, $e^+e^- \to B\bar{B}^*$, and $e^+e^- \to B^*\bar{B}^*$ in the energy range from 10.63 GeV to 11.02 GeV and the first exclusive measurement of $\Upsilon(5S) \to \Upsilon(1S, 2S)\eta$ and $\Upsilon(5S) \to \Upsilon(1S)\eta'$ branching fractions.

Deviations between $\sigma(B^{(*)}\bar{B}^{(*)})$ and $\sigma(b\bar{b})$ (Fig. 1) above 10.82 GeV (near to $B_s^*\bar{B}_s^*$ threshold) are presumably due to B_s mesons, multibody $B^{(*)}\bar{B}^{(*)}\pi(\pi)$ states and production of bottomonia with light hadrons. Positions of the minima (Fig. 1) is in agreement with the Unitarized Quark Model [6] (UQM) predictions, however the cross section there is not zero, suggesting that the UQM misses some non-resonant offset. Moreover, there is no clear narrow signal at $\Upsilon(5S)$, contradicting to the expectation that the dominant decay channel of $\Upsilon(5S)$ is $B^{(*)}\bar{B}^{(*)}$.

The results on $\frac{\Gamma(\Upsilon(5S)\to\Upsilon(1S,2S)\eta)}{\Gamma(\Upsilon(5S)\to\Upsilon(1S,2S)\pi^+\pi^-)}$ are noticeably larger than the predicted values of ~ 0.03 for $\Upsilon(2S)$ and ~ 0.005 for $\Upsilon(1S)$, calculated in the QCDME regime [7], and are comparable to the $\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$ [1], measured in a regime where QCDME is no longer valid. Fraction between η'/η transitions is significantly smaller than the value of ~ 12 predicted by the naive QCDME model and is on scale of 0.25 predicted in case of light-flavor admixture [8].

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