THE ANOMALOUS $\Upsilon(1S)\pi^+\pi^-$ AND $\Upsilon(2S)\pi^+\pi^-$ PRODUCTION NEAR THE $\Upsilon(5S)$ RESONANCE

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We report the study of $e^+e^- \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$, and $\Upsilon(1S)K^+K^-$, near the peak of the $\Upsilon(5S)$ resonance. The results are based on a data sample of 21.7 fb$^{-1}$ collected with the Belle detector at the KEKB $e^+e^-$ collider. Attributing the signals to the $\Upsilon(5S)$ resonance, the partial widths $\Gamma(\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-) = 0.59 \pm 0.04$(stat) $\pm 0.09$(syst) MeV and $\Gamma(\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-) = 0.85 \pm 0.07$(stat) $\pm 0.16$(syst) MeV are obtained from the observed cross sections. These values exceed by more than two orders of magnitude the previously measured partial widths for dipion transitions between lower $\Upsilon$ resonances.

1 Introduction

The dipion transitions between $\psi$ or $\Upsilon$ levels below the open flavor thresholds have been successfully described in terms of QCD multipole moments\cite{1}. The measurements of $\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-$\cite{234} are consistent with this picture\cite{5}. However, The spectroscopy above open flavor threshold is complex. The recent discovery of a broad $1^{--}$ state, the $Y(4260)$, decaying with an unexpectedly large partial width to $J/\psi\pi^+\pi^-$\cite{6}, has brought new challenges to the interpretation of its composition, with “hybrid” $c\bar{c}g$ (where $g$ is a gluon) and $c\bar{c}q\bar{q}$ (where $q\bar{q}$ is a color-octet light quark pair) four quark state as possibilities. The observation of a bottomonium counterpart to $Y(4260)$, which we shall refer to as $Y_b$\cite{2}, could shed further light on the structure of such particles. The expected mass is above the $\Upsilon(4S)$. It has been suggested that a $Y_b$ with lower mass can be searched for by radiative return from the $\Upsilon(5S)$, and one with higher mass through an anomalous rate of $\Upsilon(nS)\pi\pi$ events\cite{7}, scaling from $\Upsilon(4S) \rightarrow \Upsilon(1S)\pi\pi$, one expects $\Upsilon(5S) \rightarrow \Upsilon(1S)\pi\pi$ to have branching fraction $\sim 10^{-5}$.

In our studies, the rates for $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ are found to be much larger than the expectations from scaling the comparable $\Upsilon(4S)$ decays to the $\Upsilon(5S)$. Since only one center-
of-mass (CM) energy is used, one does not know whether these enhancements are an effect of the $\Upsilon(5S)$ itself, or due to a nearby or overlapping “$\Upsilon_b$” state. Throughout this proceeding, we use the notation $\Upsilon(10860)$ instead of $\Upsilon(5S)$.

2 The Analysis

This study is described in details in the reference[8]. The $\Upsilon(10860) \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$ final states are reconstructed using $\Upsilon(nS) \rightarrow \mu^+\mu^-$ decays. Events with exactly four well-constrained charged tracks and zero net charge are selected. Two muons with opposite charge are selected to form a $\Upsilon(nS)$ candidate. The two remaining tracks are treated as pion or kaon candidates. To suppress the background from $\mu^+\mu^-\gamma \rightarrow \mu^+\mu^-e^+e^-$ with photon conversion, pion candidates with positive electron identification are rejected. The cosine of the opening angle between the $\pi^+$ and $\pi^-$ ($K^+$ and $K^-$) momenta in the laboratory frame is required to be less than 0.95. The trigger efficiency is found to be very close to 100% for these final states. To reject (radiative) Bhabha and $\mu$-pair backgrounds, the data are required to satisfy either $\theta_{\text{max}} < 175^\circ$, or $2 \text{ GeV} < \sum E_{\text{ECL}} < 10 \text{ GeV}$, where $\theta_{\text{max}}$ is the maximum opening angle between any charged tracks in the CM frame, and $\sum E_{\text{ECL}}$ is the sum of the calorimeter energy.

The signal candidates are identified using the kinematic variable $\Delta M$, defined as the difference between $M(\mu^+\mu^-\pi^+\pi^-)$ or $M(\mu^+\mu^-K^+K^-)$ and $M(\mu^+\mu^-)$ for pion or kaon modes. Sharp peaks are expected at $\Delta M = M_{\Upsilon(nS)} - M_{\Upsilon(nS)}$ for $m > n$. For $\Upsilon(10860) \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$, signal events should be concentrated at $\Delta M = \sqrt{s} - M_{\Upsilon(nS)}$, since a single CM energy is used.

![Figure 1: Scatter plot of $M(\mu^+\mu^-)$ vs. $\Delta M$ for the data collected at $\sqrt{s} \sim 10.87 \text{ GeV}$, for (a) $\mu^+\mu^-\pi^+\pi^-$ and (b) $\mu^+\mu^-K^+K^-$ candidates. Horizontal shaded bands correspond to $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ (only $\Upsilon(1S)$ for (b)), and open boxes are the fitting regions for $\Upsilon(10860) \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$. The lines indicate the kinematic boundaries, $M(\mu^+\mu^-\pi^+\pi^-,\mu^+\mu^-K^+K^-) = \sqrt{s}$.](image)
Figure 1 shows the two-dimensional scatter plot of $M(\mu^+\mu^-)$ vs. $\Delta M$ for the data. Clear enhancements are observed, especially for $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ decays. The dominant background processes, $e^+e^- \rightarrow \mu^+\mu^- \gamma(-e^+e^-)$ and $e^+e^- \rightarrow \mu^+\mu^- \pi^+\pi^-$ accumulate at the kinematic boundary, $M(\mu^+\mu^- \pi^+\pi^-) = \sqrt{s}$. The events with $|M(\mu^+\mu^- \pi^+\pi^-) - \sqrt{s}| < 150$ MeV or $|M(\mu^+\mu^- K^+K^-) - \sqrt{s}| < 150$ MeV are selected. The fitting regions are defined by $1.25 \text{ GeV}/c^2 \leq \Delta M < 1.55 \text{ GeV}/c^2$, $0.69 \text{ GeV}/c^2 < \Delta M < 0.99 \text{ GeV}/c^2$, and $0.36 \text{ GeV}/c^2 < \Delta M < 0.66 \text{ GeV}/c^2$ for $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, and $\Upsilon(3S)\pi^+\pi^-$, respectively. The fitting region in $\Delta M$ for $\Upsilon(10860) \rightarrow \Upsilon(1S)K^+K^-$ is consistent with the rates measured in references $3,4$. The absence of a peak around $1.12 \text{ GeV}/c^2$ corresponding to $\Upsilon(1S)\pi^+\pi^-$ in the $\Delta M$ distribution is from the cascade decays $\Upsilon(10860) \rightarrow \Upsilon(2S)\pi^+\pi^-$ with $\Upsilon(2S) \rightarrow \Upsilon(1S)[\rightarrow \mu^+\mu^-]X$.

Signal yields are extracted by unbinned extended maximum likelihood (ML) fits to the $\Delta M$ distributions. The signal is described by a sum of two Gaussians while the background is approximated by a linear function. For the $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ modes, the remaining PDF parameters and yields of signal and background are floated in the fits. For the $\Upsilon(10860) \rightarrow \Upsilon(3S)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$ transitions, where statistics are limited, the means and widths are established based on $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$ events and fixed in the fits. We observe $325^{+20}_{-19} - 186 \pm 15, 10.5^{+4.0}_{-3.3}$, and $20.2^{+5.2}_{-4.5}$ events in the $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$, and $\Upsilon(1S)K^+K^-$ channels, with significances of $20\sigma$, $14\sigma$, $3.2\sigma$, and $4.9\sigma$, respectively. The significance is calculated using the difference in likelihood values of the best fit and of a null signal hypothesis including the effect of systematic uncertainties. The Gaussian widths of the $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ peaks are found to be $8.0 \pm 0.5$ MeV/$c^2$ and $7.6 \pm 0.7$ MeV/$c^2$, respectively, and are consistent with the MC predictions. The distributions of $\Delta M$ with the fit results superimposed are shown in Fig. 3.
ing fractions and partial widths can be extracted using ratios to the $\Upsilon(5S)$ of the $M$ could be important for the theoretical interpretation of the results. 1 agrees well with the observed distributions and the efficiencies are sensitive to both variables, events, the branching fractions ($\mathcal{B}$) and the total width of the $\Upsilon(5S)$ in the paper 1, while the open histograms show a generic phase space model. As neither model correspond to the invariant masses of the $\Upsilon(1S)\rightarrow \Upsilon(1S)K\bar{K}$, which are extracted using ML fits to $\Delta M$ in bins of $M(\pi^+\pi^-)$ or $\cos \theta_{\text{Hel}}$. The shaded histograms in the figure are the distributions from MC simulations using the model in the paper 11 while the open histograms show a generic phase space model. As neither model agrees well with the observed distributions and the efficiencies are sensitive to both variables, the reconstruction efficiencies for $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ are obtained using MC samples reweighted according to the measured $M(\pi^+\pi^-)$ and $\cos \theta_{\text{Hel}}$ spectra. Comparison of the $M(\pi^+\pi^-)$ distribution obtained here with other $\Upsilon(nS) \rightarrow \Upsilon(mS)\pi^+\pi^-$ ($m < n$) decays could be important for the theoretical interpretation of the results 11.

Assuming that signal events come only from the $\Upsilon(5S)$ resonance, the corresponding branching fractions and partial widths can be extracted using ratios to the $\Upsilon(5S)$ cross section at $\sqrt{s} \sim 10.87$ GeV, 0.302 ± 0.015 nb 11. The results, including the observed cross sections, are given in Table 1. The values include the world average branching fractions for $\Upsilon(nS) \rightarrow \mu^+\mu^-$ decays, and the total width of the $\Upsilon(5S)$ 9. The measured partial widths, of order 0.6–0.8 MeV, are large compared to all other known transitions among $\Upsilon(nS)$ states.

![Figure 3: The $\Delta M$ distributions for (a) $\Upsilon(1S)\pi^+\pi^-$, (b) $\Upsilon(2S)\pi^+\pi^-$, (c) $\Upsilon(3S)\pi^+\pi^-$, and (d) $\Upsilon(1S)K^+K^-$ with the fit results superimposed. The dashed curves show the background components in the fits.](image)

The yields for $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$ are found to be large; thus, the corresponding invariant masses of the $\pi^+\pi^-$ system, $M(\pi^+\pi^-)$, and the cosine of the helicity angle, $\cos \theta_{\text{Hel}}$, can be examined in detail. The helicity angle, $\theta_{\text{Hel}}$, is the angle between the $\pi^-$ and $\Upsilon(10860)$ momenta in the $\pi^+\pi^-$ rest frame. Figure 1 shows the $\Upsilon(10860)$ yields as functions of $M(\pi^+\pi^-)$ and $\cos \theta_{\text{Hel}}$, which are extracted using ML fits to $\Delta M$ in bins of $M(\pi^+\pi^-)$ or $\cos \theta_{\text{Hel}}$. The shaded histograms in the figure are the distributions from MC simulations using the model in the paper 11 while the open histograms show a generic phase space model. As neither model agrees well with the observed distributions and the efficiencies are sensitive to both variables, the reconstruction efficiencies for $\Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ are obtained using MC samples reweighted according to the measured $M(\pi^+\pi^-)$ and $\cos \theta_{\text{Hel}}$ spectra. Comparison of the $M(\pi^+\pi^-)$ distribution obtained here with other $\Upsilon(nS) \rightarrow \Upsilon(mS)\pi^+\pi^-$ ($m < n$) decays could be important for the theoretical interpretation of the results 11.

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Table 1: Signal yield ($N_s$), significance ($\Sigma$), reconstruction efficiency, and observed cross section ($\sigma$) for $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$ at $\sqrt{s} \sim 10.87$ GeV. Assuming the $\Upsilon(5S)$ to be the sole source of the observed events, the branching fractions ($\mathcal{B}$) and the partial widths ($\Gamma$) for $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$ are also given. The first uncertainty is statistical, and the second is systematic.

| Process     | $N_s$ | $\Sigma$ | Eff. (%) | $\sigma(\text{pb})$ | $\mathcal{B}(\%)$ | $\Gamma(\text{MeV})$ |
|-------------|-------|----------|----------|----------------------|-------------------|---------------------|
| $\Upsilon(1S)\pi^+\pi^-$ | $325^{+79}_{-49}$ | $20\sigma$ | 37.4 | $1.61 \pm 0.10 \pm 0.12$ | $0.53 \pm 0.03 \pm 0.05$ | $0.59 \pm 0.04 \pm 0.09$ |
| $\Upsilon(2S)\pi^+\pi^-$ | $186 \pm 15$ | $14\sigma$ | 18.9 | $2.35 \pm 0.19 \pm 0.32$ | $0.78 \pm 0.06 \pm 0.11$ | $0.85 \pm 0.07 \pm 0.16$ |
| $\Upsilon(3S)\pi^+\pi^-$ | $10.5^{+1.0}_{-0.7}$ | $3.2\sigma$ | 1.5 | $1.44^{+0.56}_{-0.45} \pm 0.19$ | $0.48^{+0.18}_{-0.15} \pm 0.07$ | $0.50^{+0.20}_{-0.17} \pm 0.10$ |
| $\Upsilon(1S)K^+K^-$ | $20.2^{+4.5}_{-4.5}$ | $4.9\sigma$ | 20.3 | $0.185^{+0.040}_{-0.041} \pm 0.028$ | $0.061^{+0.016}_{-0.014} \pm 0.010$ | $0.067^{+0.017}_{-0.015} \pm 0.013$ |
3 Summary

In conclusion, we report the observation of $e^+e^- \rightarrow \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ transitions, and the evidence of $e^+e^- \rightarrow \Upsilon(3S)\pi^+\pi^-$ and $\Upsilon(1S)K^+K^-$ transitions at a CM energy near the $\Upsilon(5S)$ resonance of $\sqrt{s} \approx 10.87$ GeV. Clear signals are observed at the expected CM energy, with subsequent $\Upsilon(nS) \rightarrow \mu^+\mu^-$ decay. The measured cross sections are $1.61 \pm 0.10 \pm 0.12$ pb, $2.35 \pm 0.19 \pm 0.32$ pb, $1.44^{+0.35}_{-0.45} \pm 0.19$ pb, and $0.185^{+0.048}_{-0.041} \pm 0.028$ pb for $e^+e^- \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$, and $\Upsilon(1S)K^+K^-$ transitions, respectively. The first uncertainty is statistical, and the second is systematic. Assuming the observed signal events are due solely to the $\Upsilon(5S)$ resonance, branching fractions are measured to be in the range $(0.48–0.78)\%$ for $\Upsilon(nS)\pi^+\pi^-$ channels, and 0.061\% for the $\Upsilon(1S)K^+K^-$ channel. The corresponding partial widths are found to be in the range $(0.52–0.85)$ MeV for $\Upsilon(nS)\pi^+\pi^-$, and 0.067 MeV for the $\Upsilon(1S)K^+K^-$ mode, more than two orders of magnitude larger than the corresponding partial widths for $\Upsilon(4S)$, $\Upsilon(3S)$ or $\Upsilon(2S)$ decays. The unexpectedly large partial widths disagree with the expectation for a pure $b\bar{b}$ state, unless there is a new mechanism to enhance the decay rate, such as the existence of an intermediate resonant state. Such possibility can be examined with the Dalitz plots. As shown in Fig. 5, there is no clear structure observed for the signal candidates. A detailed energy scan within the $\Upsilon(5S)$ energy region had been carried out at the end of 2007. It would help to extract the resonant spectrum, and a comparison between the yield of $\Upsilon(nS)\pi^+\pi^-$ events and the total hadronic cross section may help us to understand the nature of such signal.

Acknowledgments

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC (China); DST (India); MOEHRD, KOSEF, KRF and SBS Foundation (Korea); KBN (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).
Figure 5: The Dalitz plots, and the corresponding mass projections for $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ candidates in the signal region.

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