CHARMONIUM PRODUCTION WITH e^+e^-*

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We present a new study of double $c\bar{c}$ production in the e^+e^- continuum: many double charmonium final states are observed for the first time; the $e^+e^- \to J/\psi c\bar{c}$ cross-section is measured with reduced model dependence.

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1. Introduction

The mechanism of charmonium production in a variety of processes remains a puzzle after many years. The most striking disagreement between the theory and experiment was observed in high-p_T $\psi(2S)$ production at the Tevatron: the experimentally measured cross-section was 30 times larger than calculated within the perturbative QCD framework. Charmonium production in the e^+e^- annihilation is another process to test both perturbative and non-relativistic QCD. Theoretically, the $e^+e^- \to J/\psi gg$ process was considered to be the leading mechanism with the cross-section as high as 1 pb; the color-octet $e^+e^- \to J/\psi g$ contribution could be also significant. In contrast, none of these processes were observed experimentally so far, while the process $e^+e^- \to J/\psi c\bar{c}$ was measured by Belle with unexpectedly large cross-section [1]. In this paper we present an updated study of charmonium production with additional $c\bar{c}$ pair using a data sample of 101.8 fb^{-1} collected by the Belle detector.

2. Double charmonium production

In the published Belle paper [1] a significant peak was observed around the η_c mass in the spectrum of the mass recoiling against the J/ψ, defined as $M_{\rm recoil} \equiv [(E_{\rm CMS} - E_{J/\psi})^2 - p^2_{J/\psi}]^{1/2}$. The measured cross-section for the $e^+e^- \to J/\psi\,\eta_c$ process was an order of magnitude larger than theoretical

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predictions [2]. In an attempt to explain at least partially this discrepancy, it is suggested in Ref. [3] that processes proceeding via two virtual photons may be important and that the observed $e^+e^- \to J/\psi\,\eta_c$ signal might also include double J/ψ events. e^+e^- annihilation to $J/\psi J/\psi$ via a single virtual photon is forbidden by charge conjugation symmetry and was ignored in [1]. Given the arguments in Ref. [3], it is important to check for any momentum scale bias that may confuse the interpretation of the peaks in the $M_{\rm recoil}$ spectrum. We use $e^+e^- \to \psi(2S)\gamma$, $\psi(2S) \to J/\psi\pi^+\pi^-$ events for calibration and find that shifts in the $M_{\rm recoil}$ are less than $3\,{\rm MeV}/c^2$. The spectrum of recoil masses against the J/ψ in the data is shown in Fig. 1: clear peaks are observed around the η_c, χ_{c0} and $\eta_c(2S)$ masses. We perform a fit to this

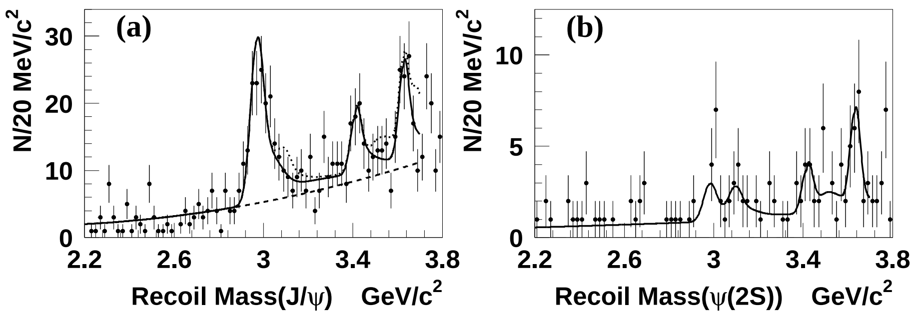

Fig. 1. The distribution of masses recoiling against the reconstructed (a) J/ψ and (b) $\psi(2S)$. The curves represent the results of the fit explained in the text.

spectrum that includes all of the known narrow charmonium states. In this fit, the mass positions for the η_c, χ_{c0} and $\eta_c(2S)$ are free parameters; those for the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$ are fixed at their nominal values. The expected line-shapes for these peaks are determined from a Monte Carlo simulation as described in our paper [1], the background is parametrized by a second order polynomial function, and only the region below the open charm threshold ($M_{\rm recoil} < 3.7\,{\rm GeV}/c^2$) is included in the fit. The fit results, listed in Table I, give negative yields for the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$; the solid line in Fig. 1 is the result of a fit with all these contributions fixed at zero. The dotted line in the figure corresponds to the case where the contributions of the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$ are set at their 90% confidence level upper limit values. The $\psi(2S)$ recoil mass spectrum is studied in a similar way and is shown in Fig. 1(b). The fit includes seven charmonium states with all masses fixed to the nominal values. The fit results are listed in the Table I. The $\eta_c(2S)$ peak is significant; only hints for η_c and χ_{c0} signals are seen. A search for $e^+e^- \to \chi_{c1(2)}\,(c\bar{c})_{\rm res}$ is performed by studying the $J/\psi\gamma$ mass

TABLE I

Summary of the signal yields, masses and significances for $e^+e^- \to J/\psi\big(\psi(2S)\big)(c\bar{c})_{\rm res}$.

	J/ψ			$\psi(2S)$	
$(c\bar{c})_{\rm res}$	N	$M\,[\mathrm{GeV}/c^2]$	σ	N	σ
η_c	175 ± 23	2.972 ± 0.007	9.9	15 ± 7	2.6
J/ψ	-9 ± 17	fixed	—	12 ± 7	—
χ_{c0}	61 ± 21	3.409 ± 0.010	2.9	18 ± 9	2.4
$\chi_{c1} + \chi_{c2}$	-15 ± 19	fixed	—	7 ± 9	—
$\eta_c(2S)$	107 ± 24	3.630 ± 0.008	4.4	31 ± 10	3.7
$\psi(2S)$	-38 ± 21	fixed	—	-4 ± 7	—

TABLE II

Summary of double charmonium production cross-sections and upper limits (at 90% CL): $\sigma(e^+e^- \to (c\bar{c})_{\rm res_1}\,(c\bar{c})_{\rm res_2}) \times \mathcal{B}((c\bar{c})_{\rm res_2} \to \geq 4\,\text{charged})$ (fb).

	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	$\eta_c(2S)$	$\psi(2S)$
J/ψ	$46 \pm 6^{+7}_{-9}$	< 8	$16 \pm 5 \pm 4$	< 18	< 20	$25 \pm 6 \pm 6$	< 64
χ_{c1}	< 18	< 18	< 18	< 18	< 18	< 18	< 18
χ_{c1}	< 20	< 20	< 20	< 20	< 20	< 20	< 20
$\psi(2S)$	$18 \pm 8 \pm 7$	< 16	$17 \pm 8 \pm 7$	< 24	< 24	$31 \pm 9 \pm 9$	< 18

distribution for the region of recoil masses from 2.8 to $3.7\,\mathrm{GeV}/c^2$. The fit to this distribution finds $2.3^{+3.0}_{-2.3}$ χ_{c1} and $0.7^{+2.0}_{-1.4}$ χ_{c2} candidates. After correction for the reconstruction efficiencies we calculate the cross-sections and upper limits for many double charmonium final states listed in Table II.

3. J/ψ production with associated charmed hadrons

In the published Belle paper [1] the $e^+e^- \to J/\psi c\bar{c}$ cross-section was inferred from the measured significant excess of D^0 and D^{*+} mesons produced in prompt J/ψ events, relying on the LUND fragmentation model. In this study we reconstruct as many as possible ground state charm hadrons to reduce the model dependence of the result. We use $D^0 \to K^-\pi^+(K^-3\pi^\pm)$, $D^+ \to K^-2\pi^+$, $D_s^+ \to K^+K^-\pi^+$ and $\Lambda_c \to pK^-\pi^+$ decay modes. To extract the number of charmed hadrons produced conjointly with J/ψ the charmed hadron signals are fitted in bins of the dileptons mass and the fit results are plotted in Figs. 2 (a)–(d). The latter distributions are fitted by a sum of J/ψ signal and second order polynomial functions. Fit results are listed in Table III. The number of $e^+e^- \to J/\psi\, c\bar{c}$ events is calculated as a sum over the D^0, D^+, D_s^+, Λ_c and $(c\bar{c})_{\rm res}$ yields corrected for the efficiency. Taking into account the total number of reconstructed J/ψ we calculate $\frac{\sigma(e^+e^-\to J/\psi\, c\bar{c})}{\sigma(e^+e^-\to J/\psi\, X)} = 0.82 \pm 0.15 \pm 0.14$.

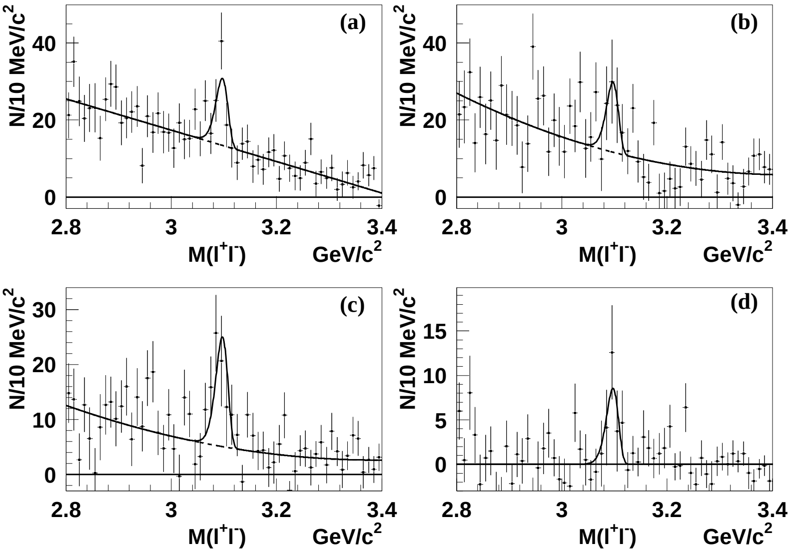

Fig. 2. Charm meson signals in bins of $M_{\ell^+\ell^-}$: (a) $D^0 \to K^-\pi^+$; (b) $D^0 \to K^-3\pi^\pm$; (c) D^+; (d) D_s^+. The curves represent the fit described in the text.

TABLE III

Summary of the signal yields and significances for $e^+e^- \to J/\psi D(\Lambda_c)X$.

mode	$D^0(K^-\pi^+)$	$D^0(K^-3\pi^\pm)$	D^+	D_s^+	Λ_c
$N_{\rm events}$	49.6 ± 13.3	53.0 ± 21.2	56.2 ± 15.4	23.8 ± 9.4	3.0 ± 4.2
σ	3.7	2.5	3.6	2.6	—

4. Summary

In summary, we have updated the results of the paper [1] and performed new searches. We have studied many double charmonium final states produced in e^+e^- annihilation. The cross-section for $e^+e^- \to J/\psi c\bar{c}$ has been calculated with better accuracy and with reduced model dependence.

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