Production of charmonium(like) states in e^+e^- interactions

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Abstract We present a search for new charmonium like states in e^+e^- annihilation using the initial-state radiation and the process $e^+e^- \to J/\psi\ D^{(*)}\overline{D}^{(*)}$. The analyses are based on a huge data sample recorded near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- asymmetric-energy collider.

Key words charmonium, new states, e^+e^- annihilation, initial state radiation

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1 Introduction

In spite of the total hadronic cross section in e^+e^- annihilation in the $\sqrt{s}$ region above the open-charm threshold was measured precisely, the parameters of the $J^{PC} = 1^{--}$ charmonium states obtained from fits to the inclusive cross section are poorly understood theoretically[1]. Moreover, in a recent study of initial state radiation (ISR) events $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ BABAR observed an accumulation of events near 4.26 GeV/c^2 in the $\pi^+\pi^- J/\psi$ invariant mass distribution, attributed to a possible new resonance, Y(4260)[2]. Later BABAR observed a different structure in the process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ at 4.32 GeV/c^2[3], denoted as Y(4350). These two states are confirmed by Belle[4, 5], and using a larger data sample Belle succeeded to observe even more complicated structure in the $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$ mass spectra. The nature of Y(4260) and Y(4350) remains mysterious: these states do not fit in the spectrum of 1^{--} charmonium states, and the observed decay modes are unexpected for a conventional charmonium states of these masses.

The solution to this puzzle and useful information on $J^{PC} = 1^{--}$ charmonium states properties can be obtained by a careful study of e^+e^- annihilation in exclusive open-charm final states. The first result on the measurement of the exclusive cross section for the process $e^+e^- \to D\overline{D}^*$ and $e^+e^- \to D^*\overline{D}^*$using a partial reconstruction technique has been recently reported by Belle[6]. In this paper we report measurements of the exclusive cross sections for the processes $e^+e^- \to D\overline{D}$ and $e^+e^- \to D^0D^-\pi^+$ using ISR that are a continuation of our studies of the near-threshold exclusive open charm production[6].

Another study presented in this paper is a search for new charmonium states in the process $e^+e^- \to J/\psi\ D^{(*)}\overline{D}^{(*)}$ at Belle. Double charmonium production in e^+e^- annihilation, first observed by Belle in 2002[7], can be used to search for new charmonium states. The study of various double charmonium final states[8, 9] demonstrated that there is no significant suppression of the production of radially excited states: the cross-sections for $J/\psi\eta_c$, $\psi(2S)\eta_c$, $J/\psi\eta_c(2S)$ and $\psi(2S)\eta_c(2S)$ are very close to each other. These studies also show that scalar and pseudoscalar charmonia are produced copiously recoiling against J/ψ or $\psi(2S)$. A new charmonium-like state, X(3940), has been already observed in the spectrum recoiling against J/ψ, and reconstructed in the $D^*\overline{D}$ final state[10].

2 Study of $e^+e^- \to D\overline{D}$ with initial-state radiation

The processes $e^+e^- \to D\overline{D}$ is reconstructed using full reconstruction of the hadronic final state, while in general, the $\gamma_{\rm ISR}$ is not required to be detected. The signature of the initial state radiation photon is a peak at zero in the spectrum of the recoil mass against the $D\overline{D}(\pi)$ system. The $e^+e^- \to D\overline{D}$ exclu-

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sive cross section is extracted from the background-subtracted $D\overline{D}$ invariant mass distribution according to the formula:

$$\sigma(e^+e^- \to D\overline{D}) = \frac{dN/dm}{\eta_{tot} dL/dm}, \qquad (1)$$

where $m \equiv M_{D\overline{D}}$, dN/dm is the obtained mass spectra, η_{tot} is the total efficiency and the factor dL/dm is the differential ISR luminosity[11]. The resulting $e^+e^- \to D\overline{D}$ exclusive cross sections, averaged over the bin width, are shown in Fig. 1 with statistical uncertainties only.

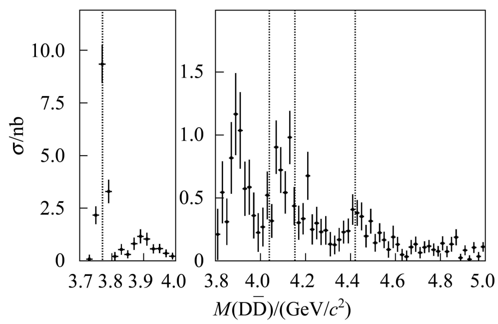

Fig. 1. The $e^+e^- \to D\overline{D}$ exclusive cross section.

The observed $e^+e^- \to D\overline{D}$ cross section is consistent with recent BABAR measurements[12] and are in qualitative agreement with the coupled-channel model predictions of Ref. [13]. This includes the visible peak at 3.9 GeV. The shape of the $e^+e^- \to D\overline{D}$ cross section for $E_{CM} > 4$ GeV is similar to that of the $e^+e^- \to D^*\overline{D}^*$ cross section[6].

We calculate the cross section ratio $\sigma(e^+e^- \to D^+D^-)/\sigma(e^+e^- \to D^0\overline{D}^0)$ for the $M_{D\overline{D}}$ bin (3.76—3.78) GeV/c^2 corresponding to $M_{D\overline{D}} \approx M_{\psi(3770)}$ to be $(0.72 \pm 0.16 \pm 0.06)$. This value is in agreement within errors with CLEO-c[14] and BES[15] measurements. The integrated over the $M_{D\overline{D}}$ range from 3.8 to 5.0 GeV/c^2 ratio $\sigma(e^+e^- \to D^+D^-)/\sigma(e^+e^- \to D^0\overline{D}^0)$ is found to be $(1.15 \pm 0.13 \pm 0.10)$ and is consistent with unity.

3 Study of $e^+e^- \to D^0D^-\pi^+$ with initial-state radiation

The $e^+e^- \to D^0D^-\pi^+$ cross section is measured with a similar method and shown in Fig. 2. A clear peak is evident around the ψ(4415) mass.

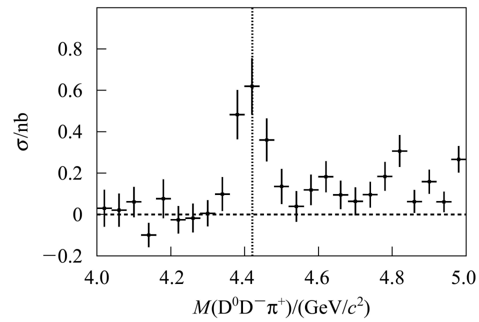

Fig. 2. The $e^+e^- \to D^0D^-\pi^+$ exclusive cross section.

To study the resonant structure in ψ(4415) decays, we select $D^0D^-\pi^+$ combinations from a ±100 MeV/c^2 mass window around the nominal ψ(4415) mass. A scatter plot of $M(D^-\pi^+)$ vs $M(D^0\pi^+)$ and its projections onto both axes are shown in Figs. 3(a), (b) and (c), respectively.

Clear signals for the $\overline{D}_2^*(2460)^0$ and $D_2^*(2460)^+$ mesons are visible in these plots. We expect positive interference between the neutral $D^0\overline{D}_2^*(2460)^0$ and the charged $D^-D_2^*(2460)^+$ decay amplitudes leading to the same $D^0D^-\pi^+$ final state for the decay of $C = -1$ state, and the scatter plot evidently agrees with this expectation: events are accumulated around the line $M(D^-\pi^+) = M(D^0\pi^+)$. We calculate the upper limit on the ψ(4415) yield in the non resonant $e^+e^- \to D^0D^-\pi^+$ process to be 18 events at 90% C.L. Assuming a phase-space-like $\psi(4415) \to D^0D^-\pi^+$ decay we calculate an upper limit on the ratio of the branching fractions of ψ(4415) decays to non-resonant $D^0D^-\pi^+$ and $D\overline{D}_2^*(2460)$ to be $\mathcal{B}(\psi(4415) \to D^0D^-\pi^+_{non-resonant})/\mathcal{B}(\psi(4415) \to D\overline{D}_2^*(2460) \to D^0D^-\pi^+) < 0.22$ at 90% C.L. From

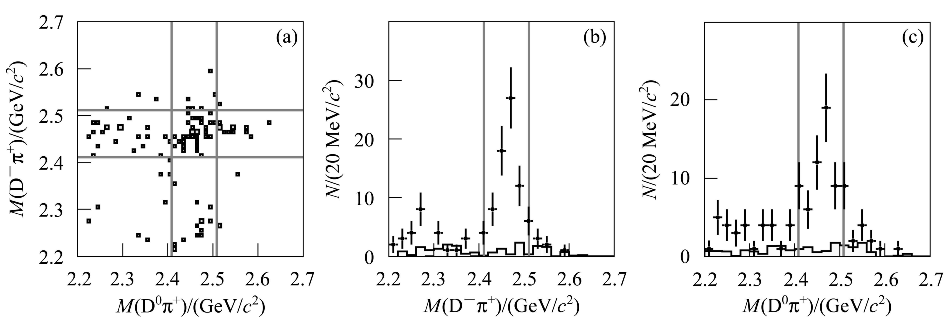

Fig. 3. (a) The scatter plot of $D^-\pi^+$ vs. $D^0\pi^+$ for the signal region in the data for $|M_{D^0D^-\pi^+} - m_{\psi(4415)}| <$ 100 MeV/c^2. (b) $D^-\pi^+$ and (c) $D^0\pi^+$ mass projections. Histograms show the normalized contributions from the M_{D^0} and M_{D^-} sidebands.

a study of the resonant structure in ψ(4415) decay we conclude that the $\psi(4415)\to D^0D^-\pi^+$ process is dominated by $\psi(4415)\to D\overline{D}{}_2^*(2460)$.

4 Study of the process $e^+e^- \to J/\psi D^{(*)}\overline{D}{}^{(*)}$

The method for reconstructing the processes $e^+e^-\to J/\psi\ D^{(*)}\overline{D}{}^{(*)}$ was described in Ref. [10]. In addition to the fully reconstructed J/ψ, only one of the $D^{(*)}$'s is fully reconstructed, and the other unreconstructed $\overline{D}{}^{(*)}$ in the event is observed as a peak in the spectra of masses recoiling against the reconstructed combination $J/\psi D^{(*)}$. As the resolution is smaller than $M_{D^*}-M_D$, the method allows the contributions from the processes $e^+e^-\to D\overline{D}$, $J/\psi D^*\overline{D}$ and $D^*\overline{D}{}^*$ to be disentangled. The $M_{rec}(J/\psi D)$ and $M_{rec}(J/\psi D^*)$ spectra in the data are shown in Fig. 4 as points with error bars for the signal $D^{(*)}$ windows; histograms show the scaled $D^{(*)}$ sideband distributions.

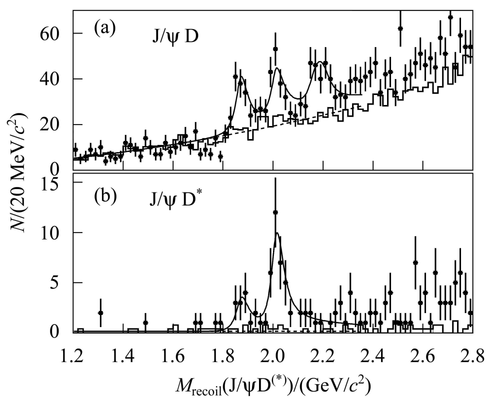

Fig. 4. The distributions of masses recoiling against the reconstructed (a) J/ψD and (b) $J/\psi D^*$ combinations in the data. The histograms show the scaled $D^{(*)}$ sideband distributions.

The signals for the processes $e^+e^-\to J/\psi D\overline{D}$, $D^*\overline{D}$ and $D^*\overline{D}{}^*$ are evident in Fig. 4(a) at the D and D^* nominal masses and at a mass ~ 2.2 GeV/c^2, respectively. The processes $e^+e^-\to J/\psi D^*\overline{D}$ and $D^*\overline{D}{}^*$ are also clearly seen in Fig. 4(b) as distinct peaks around the D and D^* nominal masses. Tagging the process $e^+e^-\to J/\psi\ D^{(*)}\overline{D}{}^{(*)}$ by the requirement $|M_{rec}(J/\psi D^{(*)})-M_{D^{(*)}}| < 70$ MeV/c^2 we thus divide each of selected J/ψD or $J/\psi D^{*+}$ combinations into two non-overlapping samples and constrain $M_{rec}(J/\psi D^{(*)})$ to the nominal mass of the corresponding D-meson in recoil to improve $M(D^{(*)}\overline{D}{}^{(*)})$ resolution.

In the data the spectra of $M(D^{(*)}\overline{D}{}^{(*)})$ are shown in Figs. 5(a), (b), (c), (d) for $D\overline{D}$, $D^*\overline{D}$, $D\overline{D}{}^*$, $D^*\overline{D}{}^*$ cases, respectively. Points with error bars correspond to the $D^{(*)}$ signal windows while hatched histograms show the scaled $D^{(*)}$ sideband distributions.

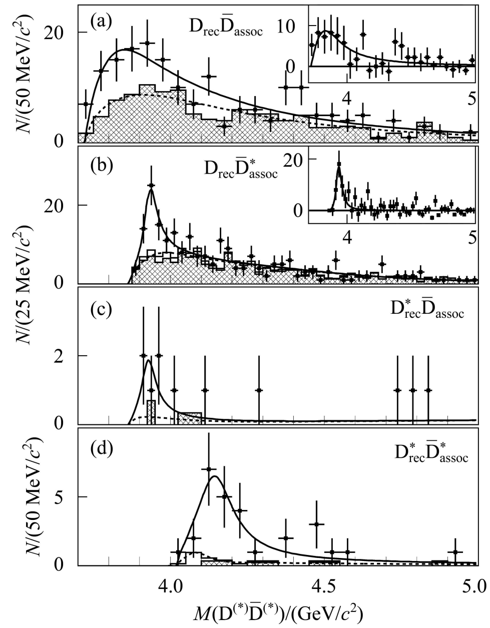

Fig. 5. The $M(D^{(*)}\overline{D}{}^{(*)})$ spectra for events tagged and constrained as $e^+e^-\to J/\psi D^{(*)}\overline{D}{}^{(*)}$.

Excesses from the signal $D^{(*)}$ window over the sideband distributions are seen around the threshold in all figures. We perform simultaneous likelihood fits to signal and sideband distributions to fix the combinatorial background shapes. The signal functions are a sum of a relativistic s-wave Breit-Wigner function and a threshold function ($\sqrt{M-M_{thr}}$) to account for possible non-resonant production. The fitted parameters of the Breit-Wigner functions and significances of the resonance contributions are listed in Table 1.

Table 1. Summary of the signal yields, masses (MeV/c^2), widths (MeV) and significances for $e^+e^-\to J/\psi(D^{(*)}\overline{D}{}^{(*)})_{res}$.

state	N_{events}	M	Γ	$\mathcal{N}_\sigma$
$X(3880)(D\overline{D})$	63^{+31}_{-25}	3878 ± 48	347^{+316}_{-143}	3.8
$X(3940)(D^*\overline{D})$	52^{+24}_{-16}	3942^{+7}_{-6}	37^{+26}_{-15}	6.0
$X(3940)(D\overline{D}{}^*)$	$5.2^{+3.4}_{-2.7}$	3934^{+23}_{-17}	57^{+62}_{-34}	2.8
$X(4160)(D^*\overline{D}{}^*)$	$23.8^{+12.3}_{-8.0}$	4156^{+25}_{-20}	139^{+111}_{-61}	5.5

A broad enhancement in $M(D\overline{D})$ is not consistent with non-resonant $e^+e^-\to J/\psi D\overline{D}$ production, however the present sample is not large enough to allow the resonant structure in this process to be determined. We have confirmed our observation of the charmonium state, $X(3940)\to D\overline{D}{}^*$, produced in the process $e^+e^-\to J/\psi\,X(3940)$ with a significance of 5.7σ including systematics. We report observation of a new charmonium-like state the X(4160) in the processes $e^+e^-\to J/\psi X(4160)$ decaying into $D^*\overline{D}{}^*$ with a significance of $5.1\,\sigma$, including the systematic uncertainty of the fit. The X(4160) parameters are $M = (4156^{+25}_{-20} \pm 15)$ MeV/c^2 and $\Gamma = (139^{+111}_{-61} \pm 21)$ MeV.

The Born cross sections for the processes $e^+e^- \to J/\psi X(3940)$ [X(4160)] multiplied by $\mathcal{B}_{D^{(*)}\overline{D}^*} \equiv \mathcal{B}(X \to D^{(*)}\overline{D}^*)$ are calculated from the fitted X(3940) and X(4160) yields with the procedure used in the previous analysis[8]. Taking into account the reconstruction efficiencies obtained from the MC simulation, the calculated Born cross-sections are:

$$\sigma(e^+e^- \to J/\psi X(3940))\mathcal{B}_{D^*\overline{D}} = (13.9^{+6.4}_{-4.1} \pm 2.2)\ \text{fb},$$

$$\sigma(e^+e^- \to J/\psi X(4160))\mathcal{B}_{D^*\overline{D}^*} = (24.7^{+12.8}_{-8.3} \pm 5.0)\ \text{fb}\ . \quad (2)$$

These values are comparable to the measured cross sections for other double charmonium final states[8, 9].

5 Summary

In summary we have studied the $e^+e^- \to D\overline{D}$ and $e^+e^- \to D^0D^-\pi^+$ cross sections and have found the $\psi(4415)$ signal in the latter process, dominated by $\psi(4415) \to D\overline{D}^*_2(2460)$; we have confirmed the observation of the charmonium state X(3940) and found the new state, X(4160), in the process $e^+e^- \to J/\psi\ D^{(*)}\overline{D}^{(*)}$. The X(4160) parameters are $M = (4156^{+25}_{-20} \pm 15)$ MeV/c^2 and $\Gamma = (139^{+111}_{-61} \pm 21)$ MeV.

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