Study of charmonium(-like) states via ISR at Belle*

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Abstract The cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $K^+K^- J/\psi$, $D\overline{D}$, $D^0D^-\pi^+$+c.c., $D^*\overline{D}$+c.c., and $D^*\overline{D}^*$ are measured using data sample collected on or near the $\Upsilon(4S)$ resonance with the Belle detector at KEKB. A peak near 4.25 GeV/c^2, corresponding to the so called Y(4260), is observed in $\pi^+\pi^- J/\psi$ final state. In addition, there is another cluster of events at around 4.05 GeV/c^2. Two resonant structures are observed in the $\pi^+\pi^-\psi(2S)$ invariant mass distribution, one at 4361±9±9 MeV/c^2 with a width of 74±15±10 MeV/c^2, and another at 4664±11±5 MeV/c^2 with a width of 48±15±3 MeV/c^2. The rich structures observed in all these final states indicate that our understanding of the vector charmonium states above the open charm threshold is still poor, let alone the other possible dynamics such as charmonium hybrids or final state re-scattering and so on.

Key words initial state radiation, cross section, charmonium, charmed mesons

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1 Introduction

The study of charmonium states via initial state radiation (ISR) at the B-factories has proven to be very fruitful. In the process $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$, the BaBar Collaboration observed the Y(4260)[1]. This structure was also observed by the CLEO[2] and Belle Collaborations[3] with the same technique; moreover, there is a broad structure near 4.05 GeV/c^2 in the Belle data. In a subsequent search for the Y(4260) in the $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^-\psi(2S)$ process, BaBar found a structure at around 4.32 GeV/c^2[4], while the Belle Collaboration observed two resonant structures at 4.36 GeV/c^2 and 4.66 GeV/c^2[5]. Recently, CLEO collected 13.2 $\rm pb^{-1}$ of data at $\sqrt{s}$ = 4.26 GeV and investigated 16 decay modes with charmonium or light hadrons[6]. The large $e^+e^- \to \pi^+\pi^- J/\psi$ cross section at this energy is confirmed. In addition, there is also evidence for $K^+K^- J/\psi$ (3.7σ) based on three events observed. Belle also measured the process $e^+e^- \to K^+K^- J/\psi$ via ISR and resonance-like structure was observed[7].

The total cross section for hadron production in e^+e^- annihilation in the energy region above the open-charm threshold was measured by the Crystal Ball[8] and BES[9] Collaborations. However, the parameters of the vector charmonium states obtained from fits to the inclusive cross section[10, 11] are poorly understood theoretically[12]. Since interference between different resonances depends on the specific final states, studies of exclusive cross sections for charmed meson pairs in this energy range are needed to clarify the situation. Recently, CLEO-c performed a scan over $\sqrt{s}$ from 3.970 to 4.260 GeV and measured exclusive cross sections for $D\overline{D}$, $D\overline{D}^*$[13] and $D^*\overline{D}^*$ final states at twelve points [14]. A measurement of $e^+e^- \to D\overline{D}$ was performed at BaBar using the ISR technique[15] with a much wider energy range. Belle used a partial reconstruction technique to perform the measurements of the exclusive cross sections including $e^+e^- \to D\overline{D}$[16], $D\overline{D}^*$, $D^*\overline{D}^*$[17], and $D\overline{D}\pi$[18] with the ISR data.

The Belle analyses are based on a data sample of about 550 $\rm fb^{-1}$ or 670 $\rm fb^{-1}$ luminosity collected near the $\Upsilon(4S)$ with the Belle detector[19] operating at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider[20]. About 90% of the data were collected at the $\Upsilon(4S)$ resonance ($\sqrt{s}$ = 10.58 GeV), and the rest were taken at a center-of-mass energy that is 60 MeV below the $\Upsilon(4S)$ peak.

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2 $e^+e^- \rightarrow h^+h^-$+charmonium

Three final states are analyzed, including $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, and $K^+K^- J/\psi$. $\psi(2S)$ is reconstructed with its $\pi^+\pi^- J/\psi$ decays, and the J/ψ is reconstructed using its leptonic decays to e^+e^- or $\mu^+\mu^-$. All the charged tracks are required to be positively identified as the particle species needed, and γ-conversion events are further removed by particle identification and invariant mass of the charged tracks. The detection of the ISR photon is not required, instead, we identify ISR events by the requirement on $M^2_{\rm rec}$ close to zero, where $M^2_{\rm rec}$ is the square of the mass that is recoiling against all the charged tracks.

Figure 1 shows the invariant mass distributions of $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$ after all the selection, together with a fit with coherent resonance terms and a non-coherent background term; and Fig. 2 shows the resulting cross sections for all the three final states, where the error bars indicate the statistical errors only. Table 1 shows the fit results, including the Y(4008) and Y(4260) from the $\pi^+\pi^- J/\psi$ mode, and the Y(4360) and Y(4660) from the $\pi^+\pi^-\psi(2S)$ mode. It should be noted that there are always two solutions in the fit to each mode, with same mass and width for the resonances but with very different coupling to

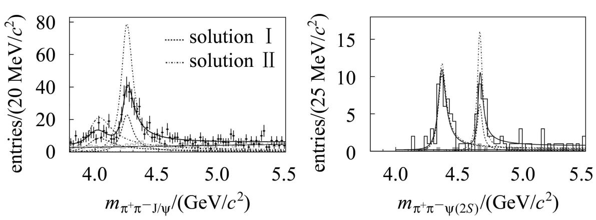

Fig. 1. The $\pi^+\pi^- J/\psi$ (upper) and $\pi^+\pi^-\psi(2S)$ (lower) invariant mass distributions and the best fit with two coherent resonances together with a background term.

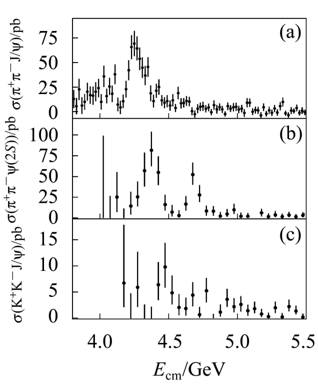

Fig. 2. The measured $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ (a), $\pi^+\pi^-\psi(2S)$ (b), and $K^+K^- J/\psi$ (c) cross sections.

e^+e^- pair ($\Gamma_{e^+e^-}$). We also fit the $K^+K^- J/\psi$ invariant mass with resonances, but the statistics does not allow us to discriminate the resonant structure.

Table 1. Fit results of the $\pi^+\pi^- J/\psi$ and $\pi^+\pi^-\psi(2S)$ invariant mass spectra. The first errors are statistical and the second systematic. M, $\Gamma_{\rm tot}$, and $\mathcal{B}\cdot\Gamma_{e^+e^-}$ are the mass (in MeV/c^2), total width (in MeV/c^2), product of the branching fraction to $\pi^+\pi^- J/\psi$ or $\pi^+\pi^-\psi(2S)$ and the e^+e^- partial width (in eV/c^2), respectively. ϕ is the relative phase between the two resonances (in degrees).

parameters	solution I	solution II
M(Y(4008))	$4008\pm40^{+114}_{-28}$	
$\Gamma_{\rm tot}$(Y(4008))	$226\pm44\pm87$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}$(Y(4008))	$5.0\pm1.4^{+6.1}_{-0.9}$	$12.4\pm2.4^{+14.8}_{-1.1}$
M(Y(4260))	$4247\pm12^{+17}_{-32}$	
$\Gamma_{\rm tot}$(Y(4260))	$108\pm19\pm10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}$(Y(4260))	$6.0\pm1.2^{+4.7}_{-0.5}$	$20.6\pm2.3^{+9.1}_{-1.7}$
ϕ [Y(4008) and Y(4260)]	$12\pm29^{+7}_{-98}$	$-111\pm7^{+28}_{-31}$
M(Y(4360))	$4361\pm9\pm9$	
$\Gamma_{\rm tot}$(Y(4360))	$74\pm15\pm10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}$(Y(4360))	$10.4\pm1.7\pm1.5$	$11.8\pm1.8\pm1.4$
M(Y(4660))	$4664\pm11\pm5$	
$\Gamma_{\rm tot}$(Y(4660))	$48\pm15\pm3$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}$(Y(4660))	$3.0\pm0.9\pm0.3$	$7.6\pm1.8\pm0.8$
ϕ [Y(4360) and Y(4660)]	$39\pm30\pm22$	$-79\pm17\pm20$

3 $e^+e^- \rightarrow$ open charm

Four final states are measured using ISR data, they are $D\overline{D}$, $D\overline{D}\pi$, $D\overline{D}^*$, and $D^*\overline{D}^*$. D^0 candidates are reconstructed using five decay modes: $K^-\pi^+$, K^-K^+, $K^-\pi^-\pi^+\pi^+$, $K^0_S\pi^+\pi^-$ and $K^-\pi^+\pi^0$. D^+ candidates are reconstructed using the decay modes $K^0_S\pi^+$, $K^-\pi^+\pi^+$ and $K^-K^+\pi^+$. To improve the momentum resolution of D meson candidates, final tracks are fitted to a common vertex applying the nominal D^0 or D^+ mass as a constraint.

The $e^+e^- \rightarrow D\overline{D}\gamma_{\rm ISR}$ signal events are selected by reconstructing both the D and $\overline{D}$ mesons, where $D\overline{D} = D^0\overline{D}^0$ or D^+D^-, and the $\gamma_{\rm ISR}$ is not required to be detected; its presence in the event is inferred from a peak around zero in the spectrum of the recoil mass against the $D\overline{D}$ system. To suppress background from $e^+e^- \rightarrow D\overline{D}(n)\pi\gamma_{\rm ISR}$ processes we exclude events that contain additional charged tracks that are not used in the D or $\overline{D}$ reconstruction.

We select $e^+e^- \rightarrow D^0D^-\pi^+\gamma_{\rm ISR}$ signal candidates in which the D^0, D^- and π^+ mesons are fully reconstructed and the $\gamma_{\rm ISR}$ is not required to be detected as for $D\overline{D}$ mode, and a requirement on the recoil mass squared against the $D^0D^-\pi^+$ system close to zero is applied. Events contain additional charged tracks that are not used in D^0, D^- or π^+ reconstruction are removed to suppress the background from $e^+e^- \rightarrow D\overline{D}(n)\pi\gamma_{\rm ISR}$ $(n>1)$ processes.

The selection of $e^+e^- \rightarrow D^{(*)+}D^{*-}\gamma_{ISR}$ signal events using full reconstruction of both the D^{*+} and D^{*-} mesons, suffers from low efficiency due to the low $D^{(*)}$ reconstruction efficiencies and small branching fractions. Higher efficiency is achieved by requiring full reconstruction of only one of the D^* mesons, the γ_{ISR}, and the slow π_{slow} from the other D^*.

The analysis of the $e^+e^- \rightarrow D^+D^{*-}$ is identical to that described above for $e^+e^- \rightarrow D^+D^-$ with the fully reconstructed D^{*+} meson replaced by a fully reconstructed D^+ meson. The requirement of a detected slow pion from the unreconstructed D^{*-} and a tight requirement on ΔM^{fit}_{rec} provides the clean $e^+e^- \rightarrow D^+D^{*-}$ signal peak in the distribution of $M_{rec}(D^+\gamma_{ISR})$.

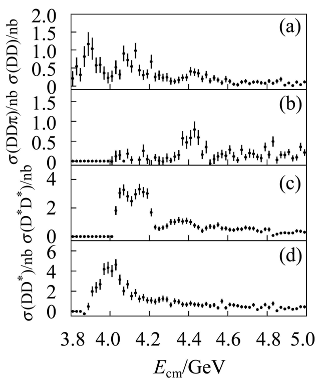

Fig. 3. The measured $D\overline{D}$ (a), $D^0D^-\pi^+ +$c.c. (b), $D^{*+}D^{*-}$ (c), and $D^+D^{*-} +$c.c. (d) cross sections.

The resulting cross sections of e^+e^- to the above modes are shown in Fig. 3. We can see the structures at the $\psi(4040)$ and $\psi(4415)$ in $D\overline{D}$ mode, and a peak at 3.9 GeV which is in qualitative agreement with the coupled-channel model prediction of Ref. [21]; and $\psi(4415) \rightarrow D^0D^-\pi^+$ is clearly seen in the $D^0D^-\pi^+$ final state. The shape of the $D^{*+}\overline{D}^{*-}$ cross section is complicated with several local maxima and minima, especially large cross section near the $\psi(4040)$ and $\psi(4160)$, while in $D\overline{D}^*$ mode, aside from a prominent excess near the $\psi(4040)$, the cross section is relatively featureless.

4 Summary and concluding remarks

With ISR technique, Belle measured cross sections of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi(2S)$, K^+K^-J/ψ, $D\overline{D}$, $D\overline{D}\pi$, $D\overline{D}^*$, and $D^*\overline{D}^*$ modes in the center-of-mass energy between 3.8 and 5—6 GeV depends on final states. These almost saturate the $e^+e^- \rightarrow$ hadrons production cross section in this energy range. The structures observed in these final states are very different from those observed in inclusive hadrons[8, 9]. This may suggest a very different picture of the charmonium states in this energy range, where the coupled-channel effect, final states rescattering, threshold effect, and possibly existing charmonium-hybrids or other exotic states such as tetra-quark state or molecular state[22, 23] may contribute.

I congratulate the organizers for a successful workshop, and I thank my colleagues at Belle for their wonderful work that are presented in this talk; special thank to Galina Pakhlova for supplying me the data for making Fig. 3 in this report.

References

1 Aubert B et al (BaBar Collaboration). Phys. Rev. Lett., 2005, **95**: 142001
2 HE Q et al (CLEO Collaboration). Phys. Rev. D, 2006, **74**: 091104(R)
3 YUAN C Z et al (Belle Collaboration). Phys. Rev. Lett., 2007, **99**: 182004
4 Aubert B et al (BaBar Collaboration). Phys. Rev. Lett., 2007, **98**: 212001
5 WANG X L et al (Belle Collaboration). Phys. Rev. Lett., 2007, **99**: 142002
6 Coan T E et al (CLEO Collaboration). Phys. Rev. Lett., 2006, **96**: 162003
7 YUAN C Z et al (Belle Collaboration). Phys. Rev. D, 2008, **77**: 011105(R)
8 Osterfeld A et al (Crystal Ball Collaboration). Report No. SLAC-PUB-4160, 1986, unpublished
9 BAI J Z et al (BES Collaboration). Phys. Rev. Lett., 2002, **88**: 101802
10 Seth K K. Phys. Rev. D, 2005, **72**: 017501
11 Ablikim M et al (BES Collaboration). arXiv:0705.4500 [hep-ex]
12 Barnes T, Godfrey S, Swanson E S. Phys. Rev. D, 2005, **72**: 054026
13 Charge-conjugate modes are included throughout this report
14 Poling R (for CLEO Collaboration). arXiv:0606016 [hep-ex]
15 Aubert B et al (BaBar Collaboration). arXiv:0607083 [hep-ex]
16 Pakhlova G et al (Belle Collaboration). Phys. Rev. D, 2007, **77**: 011103(R)
17 Pakhlova G et al (Belle Collaboration). Phys. Rev. Lett., 2007, **98**: 092001
18 Pakhlova G et al (Belle Collaboration). arXiv:0708.3313 [hep-ex], Phys. Rev. Lett. (in press)
19 Abashian A et al (Belle Collaboration). Nucl. Instr. and Methods in Phys. Res. Sect. A, 2002, **479**: 117
20 Kurokawa S, Kikutani E. Nucl. Instrum. Methods in Phys. Res. Sect. A, 2003, **499**: 1, and other papers included in this volume
21 Eichten E et al. Phys. Rev. D, 1980, **21**: 203
22 Olsen S L. arXiv:0801.1153 [hep-ex]
23 For a recent review, see for example, Swanson E S. Phys. Rept., 2006, **429**: 243; Klempt E, Zaitsev A. Phys. Rept., 2007, **454**: 1