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$e^+e^- \to$ charm cross sections via ISR*

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Abstract We discuss recent measurements of exclusive e^+e^- cross sections for charmed hadron final states near threshold performed by Belle and BaBar. The results are based on a study of events with initial-state-radiation photons in a large data sample collected with the Belle and BaBar detectors at the $\Upsilon(4S)$ resonance and nearby continuum.

Key words charmonium states, open charm threshold, cross section

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1 Introduction

The $J^{PC} = 1^{--}$ charmonium states above open charm threshold were first observed in e^+e^- annihilation almost thirty years ago. The $\psi(3770)$ was measured by MARK-I [1], DELCO [2], MARK-II [3] and BES [4, 5]; the $\psi(4040)$ and $\psi(4160)$ were measured by DASP [6]; and the $\psi(4415)$ was measured by DASP [6] and MARK-I [7]. Subsequently, although additional e^+e^- annihilation cross section measurements in the region of the ψ were reported by the Crystal Ball [8] and BESII [9], no update of their parameters were done until 2005, when a combined fit to the new data was performed by K. Seth [10]. Recently, the BESII collaboration reported new parameter values for the ψ resonances [11] derived from a global fit to their cross section measurements. To take into account the interference effect, BESII relied on the model predictions for branching fractions of ψ states into all possible two-body charm meson final states. Thus the measured parameters include model uncertainty which is difficult to estimate.

Despite the kinematic accessibility of open-charm strong decay modes for the ψ resonances, their decays to exclusive final states remained unknown for years. The first measurements of exclusive e^+e^- cross sections for charmed hadron final states near threshold were performed by Belle [12–16] and BaBar [17, 18] using initial-state radiation (ISR). ISR allows a measurement of cross sections in a broad energy range while the high luminosity of the B-factories compensates for the suppression associated with the emission of a hard photon. CLEO-c performed a scan over the energy range from 3.97 to 4.26 GeV and measured exclusive cross sections for open charm final states at thirteen points with high accuracy [19].

The discovery of unexpected charmonium-like states produced via e^+e^- annihilation with quantum numbers $J^{PC} = 1^{--}$ (the Y(4260) [20, 21], Y(4360) and Y(4660) [22, 23]) has stimulated renewed interest in measurements of exclusive cross sections for charmed hadrons. Surprisingly, no evidence for open-charm production associated with these new states has been observed.

2 Exclusive e^+e^- cross sections via ISR at B-factories

2.1 $e^+e^- \to D\overline{D}, D\overline{D}^*, D^*\overline{D}^*$ cross sections

Cross section for $e^+e^- \to D\overline{D}$ (where $D = D^0$ or D^+) were measured by Belle [12] (Fig. 1(a)) and BaBar [17] collaborations (Fig. 1(b)) by reconstructing both the D and $\overline{D}$ mesons. The obtained results are in good agreement with each other. This includes a peak around 3.9 GeV/c^2 that is seen both in Belle and BaBar cross sections spectra, which is in qualitative agreement with coupled-channel model prediction [24]. Belle and BaBar calculated the cross section ratio $\sigma(e^+e^- \to D^0\overline{D}^0)/\sigma(e^+e^- \to D^+D^-)$ at the $\psi(3770)$ peak to be $(1.39 \pm 0.31 \pm 0.12)$ and

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$(1.78 \pm 0.33 \pm 0.24)$, respectively. These values are in agreement with each other and with more accurate measurements by BES [25] $(1.27 \pm 0.12 \pm 0.08)$ and CLEO-c [26] $(1.258 \pm 0.016 \pm 0.014)$.

To measure the near-threshold $e^+e^- \to D^+D^{*-}$ (Fig. 1(c)) and $e^+e^- \to D^{*+}D^{*-}$ (Fig. 1(e)) cross sections [13], Belle used a method that achieves high efficiency by partial reconstruction of the hadronic final state. Aside from a prominent broad excess near threshold, the $e^+e^- \to D^+D^{*-}$ cross section is relatively featureless. The shape of the $e^+e^- \to D^{*+}D^{*-}$ cross section is complicated with several local maxima and minima. The obtained cross sections are compatible[1)] within errors with the $D^{(*)}\overline{D}^*$ exclusive cross section measured by BaBar [18] (Fig. 1 d, e), which measured both charged and neutral final states using their full reconstruction.

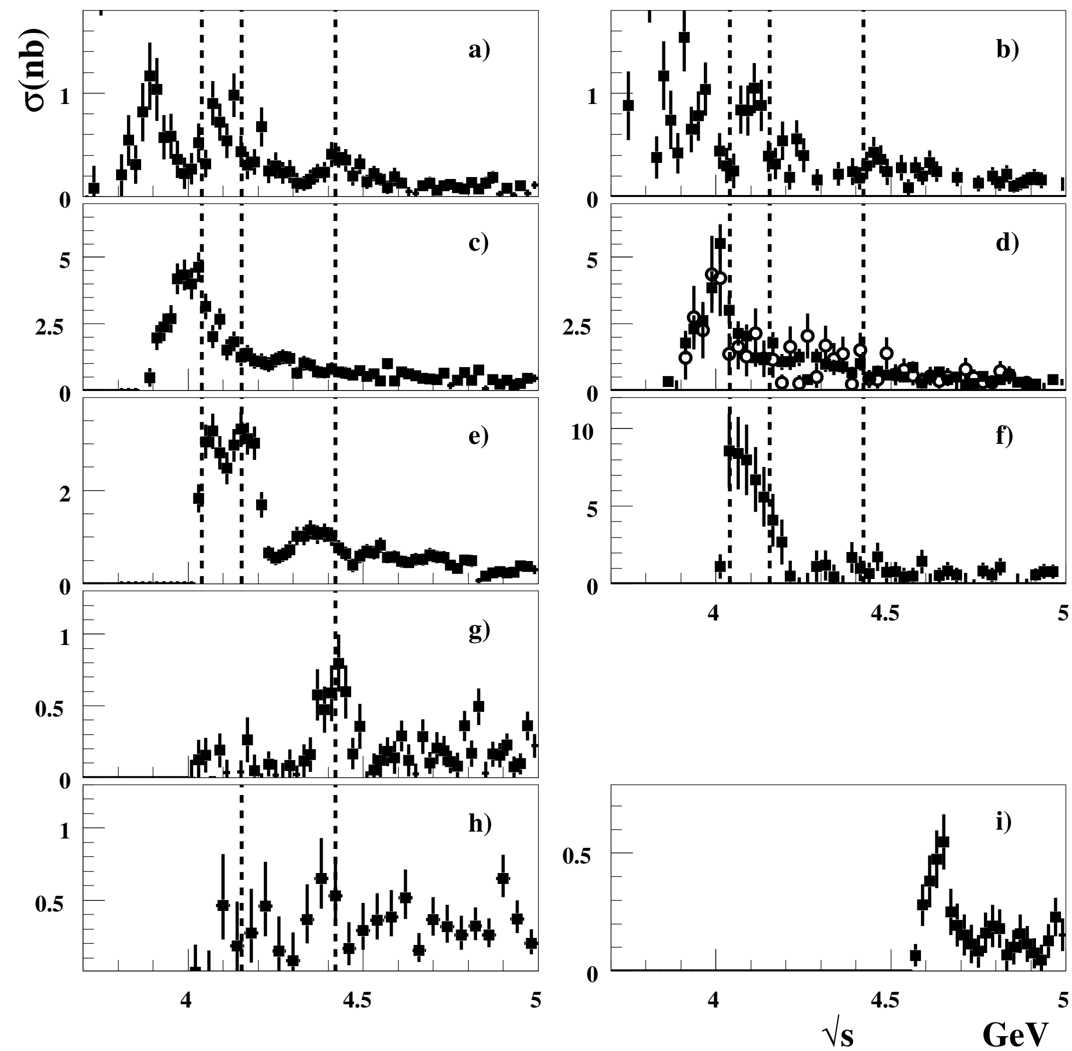

Fig. 1. The exclusive cross sections over the energy range from 3.7 to 5.0 GeV/c^2 for: a) $e^+e^- \to D\overline{D}$ measured by Belle; b) $e^+e^- \to D\overline{D}$ measured by BaBar; c) $e^+e^- \to D^+D^{*-}$ at Belle; d) $e^+e^- \to D\overline{D}^*$ (where $D = D^0$ corresponds to black points and $D = D^+$ to empty points) at BaBar; f) $e^+e^- \to D^{*+}D^{*-}$ at Belle; e) $e^+e^- \to D^*\overline{D}^*$ at BaBar; g) $e^+e^- \to D^0D^-\pi^+$ at Belle; h) $e^+e^- \to D^0D^{*-}\pi^+$ at Belle; i) $e^+e^- \to \Lambda_c^+\Lambda_c^-$ measured by Belle. The dashed lines correspond to the masses of the ψ states [27].

To estimate relative strength of ψ states decay channels BaBar performed unbinned maximum likelihood fits to the $D\overline{D}$, $D\overline{D}^*$, and $D^*\overline{D}^*$ spectra [18]. The expected ψ signals were parameterized by p-wave relativistic Breit-Wigner (RBW) functions with their parameters fixed to the PDG08 values [27]. The 3.9 GeV/c^2 structure seen in $D\overline{D}$ mass spectra was parameterized by an empiric func-

1) Since only charged final states are measured, Belle results should be scaled by a factor of two for this comparison.

tion; the non-resonant contribution was parameterized in the simplest way. An interference between the resonances and the non-resonant contributions was required in the fit. The computed ratios of the branching fractions for the ψ resonances significantly disagree with the $^3P_0$ quark model [28]. Adding the $Y(4260)$ resonance contribution to the fits (which was allowed to interfere with all the other terms) BaBar obtained the upper limits on the ratios $\mathcal{B}(\mathrm{Y}(4260)\to \mathrm{D}^{(*)}\overline{\mathrm{D}}^{(*)})/(\mathcal{B}(\mathrm{Y}(4260)\to \pi^+\pi^-\mathrm{J}/\psi)$ to at 90% C.L. presented in Table 1.

Table 1. Upper limits at 90% C.L. on the ratios $\sigma(e^+e^- \to \mathrm{Y}(4260) \to \mathrm{X})/\sigma(e^+e^- \to \mathrm{Y}(4260) \to \pi^+\pi^-\mathrm{J}/\psi)$ at $E_{\mathrm{c.m.}} = 4.26$ GeV (CLEO-c) and $\mathcal{B}(\mathrm{Y}(4260)\to\mathrm{X})/\mathcal{B}(\mathrm{Y}(4260)\to \pi^+\pi^-\mathrm{J}/\psi)$ (BaBar and Belle), where X is an open charm final state.

final state	CLEO-c	BaBar	Belle
$\mathrm{D}\overline{\mathrm{D}}$	4.0	7.6 (95% C.L.)	
$\mathrm{D}\overline{\mathrm{D}}^*$	45	34	
$\mathrm{D}^*\overline{\mathrm{D}}^*$	11	40	
$\mathrm{D}\overline{\mathrm{D}}^*\pi$	15		9
$\mathrm{D}^*\overline{\mathrm{D}}^*\pi$	8.2		
$\mathrm{D_s}\overline{\mathrm{D}}_\mathrm{s}$	1.3		
$\mathrm{D_s}\overline{\mathrm{D}}_\mathrm{s}^*$	0.8		
$\mathrm{D_s^*}\overline{\mathrm{D}}_\mathrm{s}^*$	9.5		

2.2 $e^+e^- \to \mathrm{D}^0\mathrm{D}^-\pi^+$ cross section

The $e^+e^- \to \mathrm{D}^0\mathrm{D}^-\pi^+$ cross section obtained by Belle using the full reconstruction of the hadronic final state [14] is shown in Fig. 1(g)). A clear peak is evident near mass of the ψ(4415). The study of the resonant structure in ψ(4415) decays evidently demonstrates clear signals for the $\overline{\mathrm{D}}_2^*(2460)^0$ and $\mathrm{D}_2^*(2460)^+$ mesons and positive interference between the neutral $\mathrm{D}^0\overline{\mathrm{D}}_2^*(2460)^0$ and the charged $\mathrm{D}^-\mathrm{D}_2^*(2460)^+$ decay amplitudes leading to the same final state for the decay of $C = -1$ state. Because of the strong interference effect the neutral and the charged final states were not separated in this study.

To compare mass and width of the obtained ψ(4415) signal with the corresponding resonance parameters measured in the inclusive study, Belle performed a likelihood fit to the $M_{\mathrm{D}\overline{\mathrm{D}}_2^*(2460)}$ distribution with the ψ(4415) signal parameterized by an s-wave RBW function. The significance for the signal is $\sim 10\sigma$. The obtained peak mass $M_{\psi(4415)} = (4.411 \pm 0.007(\mathrm{stat.}))$ GeV/c^2 and total width $\Gamma_{\mathrm{tot}} = (77 \pm 20(\mathrm{stat.}))$ MeV/c^2 are in good agreement with the PDG06 [29] values and the BES fit results [11]. The ψ(4415) peak cross section is calculated from the fitted RBW amplitude to be $\sigma(e^+e^- \to \psi(4415)) \times \mathcal{B}(\psi(4415) \to \mathrm{D}\overline{\mathrm{D}}_2^*(2460)) \times \mathcal{B}(\overline{\mathrm{D}}_2^*(2460) \to \mathrm{D}\pi^+) = (0.74 \pm 0.17 \pm 0.08)$ nb. Using $\sigma(e^+e^- \to \mathrm{V}) = 12\pi/\mathrm{M}_\mathrm{V}^2 \times (\Gamma_{\mathrm{ee}}/\Gamma_{\mathrm{tot}})$ the $\mathcal{B}(\psi(4415)\to \mathrm{D}\overline{\mathrm{D}}_2^*(2460))\times\mathcal{B}(\overline{\mathrm{D}}_2^*(2460)\to \mathrm{D}\pi^+) = (10.5\pm2.4\pm3.8)\%$ for the ψ(4415) parameters from the PDG06 and $(19.5 \pm 4.5 \pm 9.2)\%$ for the ψ(4415) parameters from BES fit results. Belle obtained an UL on the non-resonant (nr) $\mathrm{D}^0\mathrm{D}^-\pi^+$ production in the ψ(4415) decay to be $\mathcal{B}(\psi(4415) \to (\mathrm{D}^0\mathrm{D}^-\pi^+)_{\mathrm{nr}})/\mathcal{B}(\psi(4415) \to \mathrm{D}\overline{\mathrm{D}}_2^*(2460) \to \mathrm{D}^0\mathrm{D}^-\pi^+) < 0.22$ at 90% C.L.

2.3 $e^+e^- \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+$ cross section

The $e^+e^- \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+$ exclusive cross section measured by Belle [15] is shown in Fig. 1(h)). Belle performed a likelihood fit to the $M_{\mathrm{D}^0\mathrm{D}^{*-}\pi^+}$ distribution where the expected ψ(4415) signal contribution is parameterized by an s-wave RBW function with the mass and total width fixed to the PDG08 values [27]. To take a non-resonant $\mathrm{D}^0\mathrm{D}^{*-}\pi^+$ contribution into account a threshold function with a free normalization was used. The statistical significance for the ψ(4415) signal is 3.1σ only. An UL on the peak cross section from the fitted RBW amplitude is $\sigma(e^+e^- \to \psi(4415)) \times \mathcal{B}(\psi(4415) \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+) < 0.76$ nb at 90% C.L. Using PDG08 values of the ψ(4415) mass, total and electron widths [27] Belle found $\mathcal{B}(\psi(4415) \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+) < 10.6\%$ at 90% C.L.

To obtain limits on the decays $\mathrm{X} \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+$, where X denotes Y(4260), Y(4350), Y(4660) or X(4630) states[1)], Belle performed four likelihood fits to the $M_{\mathrm{D}^0\mathrm{D}^{*-}\pi^+}$ spectrum each with one of the X states, the ψ(4415) state and a non-resonant contribution. The X masses and total widths are fixed from Refs. [16, 27, 30]. The calculated ULs on the peak cross sections for $e^+e^- \to \mathrm{X} \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+$ processes and $\mathcal{B}_{\mathrm{ee}} \times \mathcal{B}(\mathrm{X} \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+)$ are presented in Table 2. Finally, for Y(4260), Y(4350) and Y(4660) states the ULs on $\mathcal{B}(\mathrm{X} \to \mathrm{D}^0\mathrm{D}^{*-}\pi^+)/\mathcal{B}(\mathrm{X} \to \pi^+\pi^-\mathrm{J}/\psi(\psi(2S)))$ were estimated using corresponding $\mathcal{B}_{\mathrm{ee}}\times\Gamma_i$, where Γ_i is a partial width to the observation modes. All ULs presented in Table 2 include systematic uncertainties.

2.4 $e^+e^- \to \Lambda_c^+\Lambda_c^-$ cross section

The $e^+e^- \to \Lambda_c^+\Lambda_c^-$ cross section was measured by Belle [16] using partial reconstruction (Fig. 1(i)). A clear peak is evident near the threshold. Assuming the observed peak to be a resonance, Belle obtained its parameters to be $M = (4634^{+8+5}_{-7-8})$ MeV/c^2 and $\Gamma_{\mathrm{tot}} = (92^{+40+10}_{-24-21})$ MeV. The significance including systematics is 8.2σ. The observed structure was denoted X(4630). The peak cross section is calculated

1) The latter state is discussed in the next section.

Table 2. The ULs on the peak cross section for the processes $e^+e^- \to X \to D^0D^{*-}\pi^+$ at $E_{c.m.} = m_X$, $\mathcal{B}_{ee} \times \mathcal{B}(X \to D^0D^{*-}\pi^+)$ and $\mathcal{B}(X \to D^0D^{*-}\pi^+)/\mathcal{B}(X \to \pi^+\pi^- J/\psi(\psi(2S))$ at 90% C.L., where X = Y(4260), Y(4350), Y(4660), X(4630).

	Y(4260)	Y(4350)	Y(4660)	X(4630)
$\sigma(e^+e^- \to X) \times \mathcal{B}(X \to D^0D^{*-}\pi^+)$, [nb]	0.36	0.55	0.25	0.45
$\mathcal{B}_{ee} \times \mathcal{B}(X \to D^0D^{*-}\pi^+)$, [$\times 10^{-6}$]	0.42	0.72	0.37	0.66
$\mathcal{B}(X \to D^0D^{*-}\pi^+)/\mathcal{B}(X \to \pi^+\pi^- J/\psi)$	9			
$\mathcal{B}(X \to D^0D^{*-}\pi^+)/\mathcal{B}(X \to \pi^+\pi^- \psi(2S))$		8	10	

from the fitted RBW amplitude to be $\sigma(e^+e^- \to X(4630)) \times \mathcal{B}(X(4630) \to \Lambda_c^+\Lambda_c^-) = (0.47^{+0.11}_{-0.10}{}^{+0.05}_{-0.08} \pm 0.19)$ nb; $\Gamma_{ee}/\Gamma_{tot} \times \mathcal{B}(X(4630) \to \Lambda_c^+\Lambda_c^-) = (0.68^{+0.16}_{-0.15}{}^{+0.07}_{-0.11} \pm 0.28) \times 10^{-6}$. The nature of this enhancement remains unclear. Although both mass and width of the X(4630) are consistent within errors with those of the Y(4660) supporting explanation that X(4630) ≡ Y(4660) [31], this coincidence does not exclude other interpretations for the X(4630) as a conventional charmonium state [32], a baryon-antibaryon threshold effect [33], point-like baryons [34] or a tetraquark state [35].

3 Exclusive e^+e^- cross sections from the CLEO-c energy scan

The CLEO-c collaboration performed the measurements of exclusive cross sections (at energies between 3.97 and 4.26 GeV) for final states consisting of two charm mesons, $D\overline{D}$, $D\overline{D}^*$, $D^*\overline{D}^*$, $D_s\overline{D}_s$, $D_s\overline{D}_s^*$, $D_s^*\overline{D}_s^*$, and for processes in which the charm-meson pair is accompanied by a pion [19]. The total charm cross section has been measured both inclusively and for specific two-body and multi-body final states. Internal consistency is found to be excellent. The radiatively-corrected inclusive cross section is in a good agreement with Crystal Ball [8] and BESII [9] results.

Similarly to BaBar and Belle, CLEO-c found no evidence for an enhancement of the cross section for any open-charm final states at 4.26 GeV and obtained conservative upper limits on the ratio $\sigma(Y(4260) \to X)/\sigma(Y(4260) \to \pi^+\pi^- J/\psi)$ at $E_{c.m.} = 4.26$ GeV, where X is open-charm final states. The compilation of these limits and the results obtained by BaBar and Belle are presented in Table 1.

Lack of obvious enhancement in any open-charm channel relative to other energies, which is in dramatic contrast to the clear enhancement in $\pi^+\pi^- J/\psi$, tends to disfavor the hybrid models (that predict a large coupling to the wide $D_1(2430)^0\overline{D}^0$ and a small one to $D_s\overline{D}_s$ [36]) and tetraquark interpretation (that suggests a large decay to $D\overline{D}$ or $D_s\overline{D}_s$ [36–38]).

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