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

Galina Pakhlova[1)]

Institute for Theoretical and Experimental Physics, Moscow, Russia

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 $(1.39\pm0.31\pm0.12)$ and $(1.78 \pm 0.33 \pm 0.24)$, respectively. These values

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1) E-mail: galya@itep.ru

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.

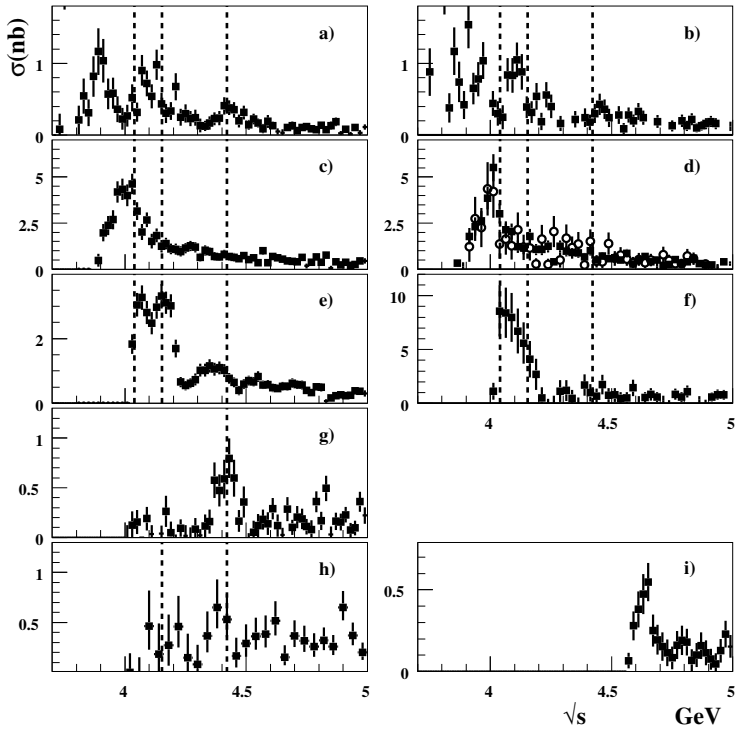

Fig. 1. The exclusive cross sections over the energy range from 3.7 to 5.0 GeV/c^2 for: a) $e^+e^- \to D\overline{D}$ measured by Belle; b) $e^+e^- \to D\overline{D}$ measured by BABAR; c) $e^+e^- \to D^+D^{*-}$ at Belle; d) $e^+e^- \to D\overline{D}^*$ (where $D = D^0$ corresponds to black points and $D = D^+$ 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 function; 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)

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

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

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

resonance contribution to the fits (which was allowed to interfere with all the other terms) BABAR obtained the upper limits on the ratios $\mathcal{B}(\Upsilon(4260)\to D^{(*)}\overline{D}^{(*)})/(\mathcal{B}(\Upsilon(4260)\to\pi^+\pi^- J/\psi)$ to at 90% C.L. presented in Table 1.

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

The $e^+e^-\to D^0D^-\pi^+$ 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 $\psi(4415)$. The study of the resonant structure in $\psi(4415)$ decays evidently demonstrates clear signals for the $\overline{D}{}_2^*(2460)^0$ and $D_2^*(2460)^+$ mesons and 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 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 $\psi(4415)$ signal with the corresponding resonance parameters measured in the inclusive study, Belle performed a likelihood fit to the $M_{D\overline{D}{}_2^*(2460)}$ distribution with the $\psi(4415)$ signal parameterized by an s-wave RBW function. The significance for the signal is $\sim 10\sigma$. The obtained peak mass $M_{\psi(4415)}=(4.411\pm0.007(\text{stat.}))$ GeV/c^2 and total width $\Gamma_{\rm tot}=(77\pm20(\text{stat.}))$ MeV/c^2 are in good agreement with the PDG06 [29] values and the BES fit results [11]. The $\psi(4415)$ peak cross section is calculated from the fitted RBW amplitude to be $\sigma(e^+e^-\to\psi(4415))\times\mathcal{B}(\psi(4415)\to D\overline{D}{}_2^*(2460))\times\mathcal{B}(\overline{D}{}_2^*(2460)\to D\pi^+)=(0.74\pm0.17\pm0.08)$ nb. Using $\sigma(e^+e^-\to V)=12\pi/M_V^2\times(\Gamma_{ee}/\Gamma_{\rm tot})$ the $\mathcal{B}(\psi(4415)\to D\overline{D}{}_2^*(2460))\times\mathcal{B}(\overline{D}{}_2^*(2460)\to D\pi^+)=(10.5\pm2.4\pm3.8)\%$ for the $\psi(4415)$ parameters from the PDG06 and $(19.5\pm4.5\pm9.2)\%$ for the $\psi(4415)$ parameters from BES fit results. Belle obtained an UL on the non-resonant (nr) $D^0D^-\pi^+$ production in the $\psi(4415)$ decay to be $\mathcal{B}(\psi(4415)\to(D^0D^-\pi^+)_{\rm nr})/\mathcal{B}(\psi(4415)\to D\overline{D}{}_2^*(2460)\to D^0D^-\pi^+)<0.22$ at 90% C.L.

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

The $e^+e^-\to D^0D^{*-}\pi^+$ exclusive cross section measured by Belle [15] is shown in Fig. 1(h)). Belle performed a likelihood fit to the $M_{D^0D^{*-}\pi^+}$ distribution where the expected $\psi(4415)$ 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 $D^0D^{*-}\pi^+$ contribution into account a threshold function with a free normalization was used. The statistical significance for the $\psi(4415)$ signal is 3.1σ only. An UL on the peak cross section from the fitted RBW amplitude is $\sigma(e^+e^-\to\psi(4415))\times\mathcal{B}(\psi(4415)\to D^0D^{*-}\pi^+)<0.76$ nb at 90% C.L. Using PDG08 values of the $\psi(4415)$ mass, total and electron widths [27] Belle found $\mathcal{B}(\psi(4415)\to D^0D^{*-}\pi^+)<10.6\%$ at 90% C.L. To obtain limits on the decays $X\to D^0D^{*-}\pi^+$, where X denotes $\Upsilon(4260)$, $\Upsilon(4350)$, $\Upsilon(4660)$ or $X(4630)$ states[1)], Belle performed four likelihood fits to the $M_{D^0D^{*-}\pi^+}$ spectrum each with one of the X states, the $\psi(4415)$ 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 $e^+e^-\to X\to D^0D^{*-}\pi^+$ processes and $\mathcal{B}_{ee}\times\mathcal{B}(X\to D^0D^{*-}\pi^+)$ are presented in Table 2. Finally, for $\Upsilon(4260)$, $\Upsilon(4350)$ and $\Upsilon(4660)$ states the ULs on $\mathcal{B}(X\to D^0D^{*-}\pi^+)/\mathcal{B}(X\to\pi^+\pi^- J/\psi(\psi(2S)))$ were estimated using corresponding $\mathcal{B}_{ee}\times\Gamma_i$, 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 $\Gamma_{\rm tot}=(92^{+40+10}_{-24-21})$ MeV. The significance including systematics is 8.2σ. The observed structure was denoted X(4630). The peak cross section is calculated

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

	$\Upsilon(4260)$	$\Upsilon(4350)$	$\Upsilon(4660)$	$X(4630)$
$\sigma(e^+e^-\to X)\times\mathcal{B}(X\to D^0D^{*-}\pi^+)$/nb	0.36	0.55	0.25	0.45
$\mathcal{B}_{ee}\times\mathcal{B}(X\to D^0D^{*-}\pi^+)$, $[\times10^{-6}]$	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	

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

from the fitted RBW amplitude to be $\sigma(e^+e^- \to X(4630)) \times \mathcal{B}(X(4630) \to \Lambda_c^+\Lambda_c^-) = (0.47^{+0.11\,+0.05}_{-0.10\,-0.08} \pm 0.19)$ nb; $\Gamma_{ee}/\Gamma_{tot} \times \mathcal{B}(X(4630) \to \Lambda_c^+\Lambda_c^-) = (0.68^{+0.16+0.07}_{-0.15-0.11} \pm 0.28) \times 10^{-6}$. 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 $X(4630) \equiv Y(4660)$ [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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